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APPRAISAL OF BARGE INTACT
STABILITY STANDARDS

Project 34-80

July 1984

Prepared for the
TRANSPORTATION DEVELOPMENT CENTRE
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Un sommaire de ce document est disponible en français:

"Evaluation des normes de stabilité intacte pour barges"

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17. Abstract The relevant stability literature is reviewed, both for vessels in general and for barges. Barge casualty records are reviewed and stability-related incidents examined. A comparison is made of barge stability standards of the United States, Great Britain, and Canada, and their bases analyzed. It is found that a significant number of barges fail to meet the level of the 1977 Canadian Interim Standard. It is concluded that capsizes safety is not yet amenable to accurate mathematical treatment. However, approaches to solutions have been made, and several modes of capsizes have been identified. Inadvertent taking on of water may be a contributing factor in some capsizes. Due to the small number of stability related casualties, the need for a Canadian barge intact stability criterion at this time is questioned. However, desirable qualities of such a criterion are given. A two-level approach is suggested. Special consideration is recommended for instances where the consequences of capsizes would be severe. Areas for further investigation are set forth.			
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17. Résumé Après une recherche documentaire sur la question de la stabilité des embarcations en général et des barges en particulier, ce rapport se penche sur les statistiques concernant les naufrages de barges et analyse ceux liés à une perte de stabilité de ces bateaux. Il établit une comparaison des normes afférentes en vigueur aux Etats-Unis, en Grande-Bretagne et au Canada et analyse les critères sur lesquels elles sont fondées. Il montre aussi qu'un nombre important de barges ne satisfont pas à la norme canadienne provisoire de 1977. Le rapport conclut que le facteur sécurité en matière de stabilité des barges n'est pas encore justiciable de traitement mathématique exact. Néanmoins, il présente un certain nombre de solutions approchées et met en évidence divers facteurs, les voies d'eau non détectées, par exemple. Il met en doute le besoin de définir dès maintenant une norme de stabilité, le nombre de naufrages attribuables à une perte de stabilité étant faible. Néanmoins, il fixe certains objectifs souhaitables à cette norme, pour l'élaboration de laquelle il suggère une approche en deux temps. Il s'agirait d'abord de réglementer les cas où les conséquences d'un chavirement seraient particulièrement sérieuses. Enfin, il met en évidence les secteurs méritant une recherche plus approfondie.			
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NOMENCLATURE

B	Beam
BM	Distance from center of buoyancy to transverse metacenter
C_b	Block coefficient
D	Depth
d	Draft
DWT	Deadweight
e_r	Dynamic stability (from 0 = 0 to 0 = 0 _m , unless otherwise stated)
f	Freeboard
f_e	Effective freeboard, taking trunk into account
GM	Transverse metacentric height above center of gravity
GM _a	Actual GM
GM _l	Longitudinal GM
GM _r	Required minimum GM
GZ	Righting arm
I_t	Transverse moment of inertia
I_l	Longitudinal moment of inertia
KB	Vertical center of buoyancy above baseline
KG	Vertical center of gravity above baseline
L	Length, in general
LOA	Length overall
LWL	Length on waterline
P	Pressure
V	Volume of displacement
Δ	Weight of displacement
θ	Roll angle from vertical
θ_m	Roll angle to maximum GZ
θ_0	Roll angle to GZ = 0

SECTION 1 - INTRODUCTION

This report covers work done under a contract with the Transportation Development Centre (TDC), Transport Canada. The project objective, as stated in the TDC Work Statement of 10 December 1980, is:

"To provide a sound basis, combining scientific analysis and empirical performance criteria, for the development of revised standards of intact stability for barges operating in Canada."

This project follows the issuance by the Canadian Coast Guard, Ship Safety Branch, on September 15, 1977 of a Canadian "Interim Standard for the Intact Stability of Unmanned Cargo Barges" [1]*, reproduced in Appendix 1. Intended for "guidance on an interim basis", the standard caused expressions of concern among barge operators as to its applicability. Ward [2] described five barges representative of the Canadian west coast fleet with "more than adequate stability" as proven by their service records. Of these five, only three complied with the Interim Standard.

It was thus appropriate and timely for a study to be made of barge intact stability.

1.1 SCOPE OF INVESTIGATION

The study was limited to barges with the following characteristics:

1. Unmanned
2. Non-self-propelled
3. Of conventional design as in common usage in Canada (excluding, for example, catamaran, submersible, or captured air bubble hulls)
4. Intact, i.e., undamaged, all hatches secured
5. Loaded symmetrically about centreline
6. Freely afloat, i.e., not anchored, moored, or aground

The main focus was on transverse stability, although one criterion governing longitudinal stability was examined.

The question of too much stability was not explored, although vessels with too high stability may be overly "stiff", resulting in undesirable accelerations. Capsize is taken as the criterion of safety; if the barge does not capsize, it is considered "safe".

* - Numbers in brackets designate references at end of paper.

SECTION 2 - PROCEDURE

A search was conducted of the relevant technical literature. Sources included North American and European periodicals, standard texts, papers from various conferences and conventions, and transactions of professional societies. Results are described in Section 3.

Next a survey of the Canadian barge fleet was made. Requests were sent to the principal Canadian owners for data concerning their fleets. Data was also drawn from the files of Robert Allan Ltd., which contain over 100 barge designs. While data was not available for all barges, a data base was compiled of about 400 barges currently operating in Canada. This sample was considered large enough to be representative of the Canadian fleet, which at the time of writing numbers approximately 850. Section 4 contains results of this survey.

Barge casualty data was gathered from several sources, including Canadian Coast Guard computer printouts and Robert Allan Ltd. files. Interesting information also came from less formal sources, such as newspaper clipping files and conversations with people in the industry. Results are in Section 5.

Stability criteria from several national authorities, IMO, and other sources were reviewed. The first part of Section 6 presents the general background for these criteria and reviews each of them in detail. The "national" criteria are then analyzed and evaluated in the second part of Section 6.

Part of the evaluation of intact stability criteria involved assessing their impact on existing barges. A set of 30 example barges was selected from Robert Allan Ltd. design files. The selection was intended to represent barges of various types and sizes. Designs dating from 1961 to 1982 and ranging from 1,400 t to 17,000 t deadweight were used; particulars are shown in Table 1. Each barge was then assumed to be loaded with its intended cargo to a "realistically conservative" condition. While almost any barge theoretically can be loaded to have inadequate stability, the conditions chosen were among the most conservative (i.e. with minimal stability) which could be envisioned with the barges carrying typical cargoes and loaded in a manner consistent with common practice.

A righting arm curve was developed for each barge using a computer program from Wolfson Unit, Southampton University, England. This program computes hydrostatics and righting levers, using as input the hull shape as defined by a modified table of offsets. Defining each hull shape is a somewhat laborious process. This was streamlined by adopting two "parent" barge hull forms for which the hull shapes were defined. Then for each of the remaining barges, a suitable parent hull was selected and stretch factors applied to that parent to yield a new hull. This new hull, while based on the parent, had the same length,

breadth, depth, and draft as the barge being examined. Righting arm curves were then computed for this new hull. As a check on the accuracy of this process, one of the parent hulls was approximated by stretching the other parent's lines. Righting arms for the original barge and the approximated version are shown in Figure 1. It can be seen that the resulting difference in GZ is about ten percent; the difference in dynamic stability up to the angle of maximum GZ is about 15 percent. While such differences are not insignificant, it was felt that they could be minimized by choosing a parent hull form which closely resembled the barge being studied. The parent hull used in Figure 1 is quite different in shape from the barge to which it was applied. Also, defining each hull of interest would have taken a prohibitive amount of time for this project.

For typical barge righting arm curves, see Figure 3.

The conclusions drawn from the study are given in Section 7, and recommendations are presented in Section 8.

SECTION 3 - LITERATURE REVIEW

This section is divided into two parts. The first reviews the literature concerned with stability of ships in general, while the second covers sources which address barges specifically.

3.1 GENERAL STABILITY CONSIDERATIONS

At present there is no generally accepted method for predicting the safety of a vessel against capsizing. As Krappinger [3] said:

"If a naval architect who tries to find out what to do in order to make ships safe against capsizing or if an administrator who looks for some advice how to improve stability regulations decides to study the literature on the forementioned and other methods they will soon make a rather bewildering experience."

The "bewildering experience" is that there is little agreement as to how to relate the characteristics of a vessel to its safety from capsizing, in the general case.

While many researchers have looked into the question, and while several criteria have been proposed, the mechanisms involved in capsizing are still poorly understood. However, specific avenues of investigation have yielded results as described below. The basic principles of intact stability are presented in [4]. A general overview of stability research is given by Bird and Odabasi [5].

St. Denis and Pierson, in 1953 [6], introduced naval architects to the notion of describing ocean waves on a statistical basis as a sea spectrum. This statistical description implied that one could never predict the highest wave that a storm might ever generate; one could say only what the probability was of encountering a high wave. One could also say what the average wave height might be, or the average height of the one third highest waves, one tenth highest, etc. If the response of a vessel to regular waves of any given wave height were known, one could then calculate the probabilities of various responses occurring in a random seaway, as illustrated by Michel [7]. For example, if the roll angle of a vessel were known as a function of height of regular waves, the probability of the vessel's capsizing could be calculated for each sea state. Thus no vessel is considered certain of not capsizing; there is always a finite probability, however small, that capsizing (or any other response) might occur.

The principles of vessel motions are given by Lewis [8].

An important contribution towards determining the required ship coefficients for motion prediction was made by Salvesen, Tuck, and Faltinsen [9]. Their "strip theory", as it is known, was thought to apply only to hulls with high length/beam (L/B) ratios. However, Kim, Chou, and Tien [10] indicate that strip theory can be applied to barges with L/B as low as 2.5.

Using this theory as a foundation, several researchers have proceeded by writing the equations of roll motion, solving them, then examining the solution for areas of instability. This "deterministic" approach has met several difficulties, stemming both from deficiencies in the mathematics of coupled nonlinear systems and from inadequate understanding of the physical phenomena. Some areas of difficulty are:

1. **Nonlinearity.** The roll response of a vessel is not linear with wave height. For example, Figure 2, from Fujii and Takahashi [11], illustrates the nonlinear response of a tanker model to regular seas. Thus the resulting differential equations of motion are nonlinear, particularly at the large roll angles of interest. Hasselman [12] presented a transform method; Vassilopoulos [13] suggested using Wiener's theory for nonlinear systems to handle uncoupled equations; Dalzell [14] found, through computer simulation of random, nonlinear rolling, that approximating such processes by linear systems is invalid. Wright and Marshfield [15] gave three methods for finding approximate solutions.
2. **Coupling.** A vessel's motions are not independent of each other. Paulling and Rosenberg [16] found heave, pitch and roll to be strongly coupled, and showed experimentally that excitation in the heave mode could produce large rolling motions. Haddara [17] investigated coupled sway, roll, and yaw. Kure and Bang [18] found that coupling between sway and roll contributed to the capsizing of a 59 m tanker in the Baltic Sea, while Blocki [19] examined heave/roll and pitch/roll coupling, although with a linearized Mathieu equation.

The general case, that of six degrees of freedom (roll, pitch, yaw, surge, sway, and heave) with nonlinear coupling, is a daunting mathematical problem and the solution is not known. A broad review of research is presented by Odabasi and Hearn [20].
3. **Large motions.** Capsizing involves extreme motions, an area where the forces affecting vessel behavior are still poorly understood. The effect of water on deck, for example, is still not well defined, although Dudziak [21], Faltinsen [22] and Dillingham [23] have made important contributions; see also Caglayan and Storch [24]. Another area requiring further study is the variation in added mass and damping at extreme angles of heel.
4. **Stochastic process.** A vessel encounters many different waves at various initial conditions. A given wave might or might not cause capsizing, depending on the vessel's heading and motions at the time of encounter. These initial conditions are not deterministic, but are rather statistically described [25].

5. **Rarity of event.** The fact that capsizes occur only rarely means that to accurately predict the probability of their occurrence, a very large data sample is required. Kastner [26] showed that in model tests, for example, even a run time of six hours would yield an estimate of capsizing probability "only at one model condition and (with) a poor statistical precision." Additional work on the statistics of extreme values was done by Ochi and Bolton [27], [28], and by Ochi [29].

Although the sea spectrum/equation of motion approach has not led to the hoped-for success, namely, quantitative calculation of the probability of capsize, it has provided the theoretical framework for such a calculation. Also, the difficulties encountered have identified those areas in need of further investigation.

A second avenue explored in Germany by Wendel, Grim, Arndt, Roden, and others is the variation in a vessel's restoring moment in a seaway. It was found that a particularly dangerous situation exists for some ships in a following or quartering sea. When a wave crest passes near midships, restoring moment is decreased. Maximum loss in restoring moment (i.e., least stability) occurs when the length and speed of the wave are about equal to those of the ship. Kastner [25], Paulling [30], and Paulling, Oakley, and Wood [31] gave theoretical and experimental confirmation. A more illustrative description is given in Bovet, Johnson, and Jones [32]. Such a phenomenon may explain why some vessels are lost in relatively moderate sea states (e.g. Beaufort 5-7).

With the advent of sufficient computing capacity, examining a vessel's motion in the time domain has become feasible. Initial conditions for the vessel (e.g. upright) are specified and a small time step (e.g. 0.2 seconds) is assumed. Then the wave profile is determined from sea spectrum theory and the resulting forces on the vessel computed, using hydrostatic methods. The vessel's response is then a small change in heel, trim, etc. Then for the vessel in this new condition, another time step is taken and the process repeated. Time domain solutions may be termed "model testing by computer", since the output is a time history of the vessel's behaviour.

Accuracy of the output depends on how well the assumed input parameters reflect the real-life situation. In particular, the wave profiles and damping coefficients used will have a great influence on the result.

References [31] and [32] report results for a time domain simulation of a cargo liner in following seas, with at least qualitative agreement with model tests. Morrall [33] used the method on a trawler in beam seas.

The above three approaches (equation of motion analysis, variation in restoring moment, and time domain simulation) all depend on a statistical description of the sea environment. To obtain a reliable and realistic description, long term monitoring of the ocean at the site of interest is required. Data for the North Atlantic is now available, but a scarcity of data exists for most other portions of the world's oceans. Hogben and Lumb [34] is a good source of available ocean wave data. Other sources included Roll [35] and Sellars [36].

Given the difficulties outlined above, researchers sought other ways of handling the problem. Krappinger [3] suggested what might be termed a "scenario" approach. He described several capsize scenarios, such as during a turn, in a following sea, etc. A ship would be considered safe if it did not capsize in any of these discrete situations. Thus the problem was reduced from determining roll angle as a general function of environmental and vessel parameters, to an examination of several specific scenarios, each more amenable to solution. The work of Dorin, Nikolaev, and Rakhmanin [37] supports this notion and categorizes various factors influencing stability.

Concurrently, Paulling et al. [31] identified, from model experiments, three modes of capsizing:

1. pure loss of stability, through righting arm reduction when the ship is on a wave crest;
2. broaching, through loss of directional control in short, steep, following seas; and
3. low-cycle or parametric resonance, where periodic oscillations in righting arm induced capsize.

A further step was taken by Odabasi [38]. He showed that, although an explicit solution to the equation of motion is still unknown, information concerning the stability of its solution can be obtained through Lyapunov's Direct Method. Using a relatively sophisticated mathematical treatment, he related vessel rolling motion to ship parameters and environmental conditions. Although simplifying the problem by neglecting coupling, shipping of water, randomness of the sea state, and shifting of cargo, Odabasi formulated mathematical conditions for safety from capsize. From these, a proposed new intact stability criterion was developed. For further treatment of this mathematical technique see [39].

3.2 BARGE STABILITY

Several authors have addressed the specific problem of barge stability.

1. Glostén and Heyrman [40]

German, in discussing [40], offered the opinion that,

"...since safety of life at sea is not a consideration and hazard to property is less than for corresponding self-propelled vessels, it would seem that the criteria for minimum stability should be less severe than for self-propelled vessels."

The authors responded with the observation that,

"...in general, angles of roll of barges of the usual form with high breadth-to-draft ratios have been moderate even in rough water. While large metacentric heights are usually associated in the minds of naval architects with violent, near-synchronous rolling, barges more nearly approach the extreme case of the raft which follows the wave slope.

"This inherent, high degree of stability makes Mr. German's question of proper stability criteria for barges somewhat academic. However the authors are of the opinion that it is essential where inadequate stability may be a problem, that there should be no relaxing of the criteria which will ensure a safe voyage. An unstable barge is a potential hazard and moreover may fail to deliver the goods."

It should be noted that this paper was published before the 1966 Load Line convention allowed a reduction in freeboard for unmanned barges.

2. Young [41] and Snyder [42]

A series of experiments with barge models in regular and irregular beam seas was conducted at the University of Michigan for the U.S. Coast Guard. These experiments attempted to establish whether a model would capsize, given values for draft/depth, dynamic stability, and significant wave height. The following conclusions were drawn from this study:

- a. "The dependency of freeboard and dynamic stability on capsizing is not clearcut," [42], p. 15. For several conditions, the model capsized at certain wave heights but remained safe in higher waves.
- b. The influence of water on deck was pronounced. Sometimes the water appeared to reduce rolling, other times it appeared to cause capsize.
- c. "An important parameter seems to be the relation between the barge's natural roll period and the characteristic period of the incident wave spectrum," [42], p. 15. Evidence of resonance in rolling was present in several tests.
- d. Severe nonlinearities were observed in the roll motion, calling into question the use of regular wave responses to predict motions in an irregular sea, [41], p. 16.
- e. "The presence of deck cargo does effect the model's survivability. It was not possible to capsize the model with the solid [wood] deck cargo," [42], p. 16.

- f. Whenever the model capsized, it was always into the advancing waves. For seas coming from starboard, capsizes occurred with the model rolling the starboard side under.

Model test runs were limited to 15 to 20 minutes each (full scale time). In view of Kastner's work [26], this may have been too short a time from which to draw statistically significant conclusions, and it may be one factor in the lack of clear correlation between survivability and dynamic stability or wave height.

3. **Bovet, Johnson and Jones [32]**

The authors, all staff members of the U.S. Coast Guard, commented on the origins of the U.S.C.G. stability criterion for deck cargo barges. (The "weather criterion" and "Rahola criterion" mentioned below are described in Section 6.)

"Until the 1966 International Load Line Convention, barges were presumed to have sufficient intact stability. The 1966 ILLC stated that unmanned barges could have a 25-percent reduction in freeboard below that required for ships. This raised the question of whether barges still have sufficient stability with this reduced freeboard. Barges could now have draft-to-depth ratios in excess of 0.80. As a result of a study of typical deck cargo barges by the Coast Guard, a twofold stability criterion was established. A deck cargo barge differs markedly from a ship in terms of its vertical center of gravity, hull form, and draft-to-depth ratio. Therefore, the barge criterion requires barges to meet the weather criterion and to have an area of at least 15 ft deg (.08 m rad) under the righting arm curve at all drafts as well. The 15 ft deg is again an adaptation of the Rahola criterion, recognizing that the maximum righting arm for barges does not occur at 30 or 40 deg of heel, but at some lesser angle."

They admitted, however, that this criterion lacks the basis of adequate understanding of the capsize phenomenon.

"What is the relationship between freeboard and stability for barges? How much intact stability does a barge require? These questions lie unanswered."

4. Kossa [43]

Writing as a practicing naval architect, Kossa reviewed the U.S.C.G. and IMCO criteria. He described measures of available stability, including initial GM, dynamic and damaged stability. Roll motions were discussed, both as simple harmonic motions in regular waves and as resulting from the sea spectrum approach. While little new knowledge was presented, the paper examined barge stability from a practical viewpoint. Kossa noted that "the loading condition with the deepest anticipated draught is likely to have least stability," although a shallow draft condition with a high centre of gravity should also be checked.

5. Talbot [44]

In this theoretical examination of deck cargo barges loaded with aggregate, Talbot presented righting arm curves for a variety of assumed loading conditions. The decrease in dynamic stability with increasing draft was illustrated. He argued that increasing the height of the cargo box sides is detrimental to stability, as the load of aggregate is retained on board for larger heel angles and not shed over the top of the box. It is apparently assumed that the box sides are permeable to water and that heeling is at a slow rate so that inertial effects on the load are ignored.

Elimination of box sides results in early shedding of cargo and greater dynamic stability. The paper concluded, "Do not load beyond a safe draft," but no definition of "safe" was offered.

6. Ward [2]

In covering selected topics concerning Canadian west coast barges, the author devoted one section to barge stability. Ward refers to the "extremely low incidence of capsizing in both coastal and offshore barge operations".

"To the author's knowledge there has been absolutely no capsizing of Canadian barges in offshore service attributable to lack of initial stability."

Barge stability criteria of the United States and the United Kingdom are reviewed and compared to the Canadian Interim Standard. Six deck cargo barges in domestic coastal service (see Table 2) are presented as "a most reliable sampling of the Canadian west coast barge fleet." The righting arm curves of these barges are given in Figure 3, reproduced from [2].

"It can be seen that four of the barges meet the USCG criterion, none of them fully comply with the U.K. criterion, and only three meet the Canadian Interim Standard."

"The conditions shown represent actual loads. Of course combinations of load heights and cargo densities can be generated to meet any set criterion; however, with the exception of the barge represented by Curve 6, all the vessels shown have been in service for many years in virtually every sea state encountered in these waters and it may be concluded, with some confidence, that they have more than adequate stability.

"Barge 6 is one of a series of gravel barges referred to earlier and which probably should not and would not be used at that particular loading on voyages requiring the possession of a Load Line Certificate."

It should be noted that the dynamic stability of Barge 5 fails to meet the Canadian Interim Standard by only 0.2%. However, the author's point, that barges which have proven satisfactorily stable in service should not be unduly restricted, remains valid.

7. Ward [45]

In this subsequent paper, Ward presented the righting arm curves for four barges (see Table 3). Barge 7 is apparently the same as Barge 3 in Reference [2]. The remaining three barges in [45] appear to differ from those in [2], at least in terms of loading conditions and righting arms.

"All conditions shown are factual and have been chosen because cross curves of stability were available for those particular vessels.

"They are probably representative of quite conservative loadings, sometimes as in the case of the lumber barge an additional layer of packages will be loaded, this being left to the judgement of the Cargo Loading Supervisor, a person conversant with the stability characteristics of these barges at various loading heights and differing wood species.

"There is no doubt in my mind that the hundreds of loadings and tens of thousands of sea miles logged with these barges without any problem are indicative of adequate intact stability."

"A built-in insurance policy for deck cargo barges is that at more excessive angles of heel the upper layers of the deck cargo will be shed thus increasing the barge's freeboard and stability. This aspect was explored in considerable depth by Talbot at the 2nd B.C. Towboat Owners Conference in 1978. [44]

"While there is a colossal amount of experience in the operation of unmanned barges on this coast the written documentation is somewhat scant."

As shown in Table 3, Barges 7 and 8 fail to meet the the Canadian Interim Standard of .08 m rad, while Barges 9 and 10 comply. Several questions arise. To what extent are these barges representative of the Canadian fleet? What casualties resulting from inadequate stability have occurred? What factors, other than dynamic stability, might influence the probability of capsizing? These questions are dealt with later in this report.

8. **Hutchison [46]**

While Hutchison treats vessel risk analysis in general terms, Appendix 1 of [46] analyzes the proposed voyage of a barge, the "Foss 245", from Norfolk, Virginia to Astoria, Oregon. Factors considered include route, wave climatology, seamanship, and vessel response. Results are expressed as the probability of exceeding certain response values. For example, it is calculated that there is a probability of 1% that this barge would roll greater than 28 degrees at least once during the voyage; the probability of exceeding 25.3 degrees is 10%.

Important to the accuracy of the results is the accuracy of the input data, including sea state description and method for vessel motion predictions. The same problems noted above (e.g. nonlinearity) also apply here. The technique of risk analysis, however, is not dependent on any particular motion prediction method. Two points of special interest are brought out.

- a. The method combines a description of the vessel with a description of the environment to yield a statistical description of a response (e.g. roll angle).
- b. The factor of seamanship is addressed in a quantitative manner. It was found that seamanship can significantly influence the risk of experiencing high accelerations.

9. **Jones and Turner [47]**

The need for uniform intact stability criteria is outlined, and questions requiring further investigation are put forward.

Of primary concern are deck cargo barges carrying heavy cargoes offshore. The observation is made that,

"With ordinary ships, the criteria have been built up from analysis of ship losses. This method cannot be used here since, as far as we are aware, there have been no losses, or, at least, insufficient to be used as the basis of deducing suitable criteria."

10. Szajnberg, Greiner, Chen, and Rawstron [48]

The authors discuss various problems encountered in the transportation of large offshore structures on deck barges. Particulars are given for 20 barges of 73 to 198 m in length and capable of carrying about 5,000 to about 70,000 DWT.

Of particular interest are the requirements of various regulatory bodies. Environmental (wind and wave) loads and standards for intact and damaged stability, as defined by these bodies, are tabulated. A comparison of criteria based on wind speed is given; it is shown that some criteria are very sensitive to the assumed wind speeds.

The authors comment on the necessity to balance adequate stability with acceptable motions and accelerations:

"It has long been known that a vessel with a high degree of stability will have stiff or jerky motions, because as the GM of the vessel is raised, the lower its natural period becomes. This tradeoff between dynamic stability and motion acceleration is the practical problem that confronts the designer in transportation analysis."

They conclude,

"The designer's concern, then, is that of motion control rather than maximum stability."

11. Hutchison and Nichol [49]

Further to Hutchison's paper on prevoyage risk analysis [46], a barge was fitted with instrumentation to monitor its motions during a voyage. Details of the installation are described. Three mutually orthogonal accelerometers were mounted to give surge, sway, and heave accelerations. Measured maximum accelerations were significantly less than those predicted. The greatest values measured were 0.040 g surge, 0.080 g sway, and 0.095 g heave.

Accelerometer readings were transmitted to the tug's pilothouse to provide real-time barge motion monitoring. It was hoped that such information would provide valuable feedback to the tug skipper and crew in their attempts to reduce motions. The authors conclude that the monitoring system "appears to have been an effective aid in reducing the severity of motions...". No reason is offered for the discrepancy between predicted and measured accelerations.

SECTION 4 - CANADIAN BARGE FLEET

4.1 SIZE

The Canadian barge fleet is concentrated in four marine areas: Atlantic Coast, Great Lakes/St. Lawrence River, Mackenzie River/Arctic, and Pacific Coast. Darling [50] gives the count of barges in 1968 shown in Table 4.

The "Inland" group is made up largely of barges operating in the Mackenzie River and other northern areas. This portion of the fleet comprised 149 barges with 84,000 t DWT in 1972 [51], while Canadian barges on the Great Lakes numbered 29 with about 70,000 t total DWT [52].

Ward [2] gives data for the number of barges constructed in B.C. annually for 1970 - 1979.

Based on the above data and on the 1982 List of Shipping [53], an estimate was made of the Canadian barge fleet for 1982. This estimate is shown in Table 5. This estimate does not include small barges, i.e., of less than about 200 t DWT.

4.2 TYPES

Barges may be classified by the manner of cargo stowage. Examples of various stowage types include:

1. Tank barges, where tanks (usually for liquids) are arranged under deck.
2. Deck cargo barges, which carry various cargoes loaded on the main deck. Often, but not always, some type of fence is provided to restrain cargoes from spilling off the barge. A wide variety of cargo is carried on deck barges, including aggregate, logs, lumber, railcars, machinery, and wood chips.
3. Covered barges, a variation of deck barges. These have an enclosed house within which cargo is stored. Loading and discharge are usually with fork lift trucks or front end loaders.
4. Hopper barges, which carry bulk cargoes in hoppers either built into the hull or mounted above deck. The hoppers usually feed into conveyors for discharge.

Sometimes a barge may be a combination of the above types. For example, a hopper barge (type 4) might also have a covered house on deck (type 3), or a barge might have tanks below deck (type 1) and load railcars on the main deck (type 2).

Many barges carry principally one type of cargo and are often designated by that cargo, rather than by the manner of stowage. Chip barges, a type of deck cargo barge, are designed and built to carry wood chips. Other barges designated by cargo carried include log, limestone, pulp, and railcar barges. Several selected examples of different barge types are described below.

1. Log barge. The "Island Forester" (Figure 4) carries up to about 16,000 t of logs on deck. Two cranes mounted on the barge provide a self-loading capability. Logs are discharged by filling ballast tanks on one side of the barge to cause gradual heel. When the angle of heel is great enough, the logs slide off the deck into the water in a sudden and dramatic manner. The empty barge is then de-ballasted to an even keel condition. Log barges are one of the largest types of barge, ranging up to about 18,000 t DWT.
2. Covered barge. The "Nanoose Carrier" (Figure 5), 6,400 t DWT, carries newsprint on her main deck under the protection of a steel deckhouse. This barge, one of a series of four operating on both the Atlantic and Pacific coasts, has been modified to carry oil in the hull tanks on the return leg of voyages to U.S. ports.
3. Deck barge. Figure 6 shows the plans of a typical open deck cargo barge of 3,600 t DWT. A cargo fence is arranged on each side. The fence fairs into a bulwark forward and is open at the stern.
4. Dump scow. The barge shown in Figure 7 is constructed in two intact halves which are hinged together at the deck level. Cargo stowed in the open hold is dumped when hydraulic cylinders push the two halves open at the bottom. This barge carries 5,500 t of cargo.

4.3 OPERATORS

By far, the two largest Canadian barge operators are Seaspan International Ltd. and RivTow Straits Limited, both of Vancouver. Seaspan operates about 250 barges, totalling 550,000 t DWT, while RivTow operates about 80 barges with about 140,000 t total DWT. Chip barges comprise almost two-thirds of Seaspan's fleet and about one-third of RivTow's. A more detailed breakdown of these two fleets is presented in Tables 6 and 7.

The largest operator of inland barges is Northern Transportation Co. Ltd., a Crown Corporation, which operates tugs and barges on the Mackenzie River, Hudson Bay, and other northern waters. In 1972 the company was reported to have 116 barges totalling 70,000 t DWT in service [51]. This represented 78% of the barges and 83% of the deadweight capacity of the northern barge fleet.

On the eastern seaboard, J. D. Irving Ltd. of Saint John, New Brunswick has 17 barges totalling 17,900 GRT [53] (estimated DWT approximately 34,000 t).

4.4 DIMENSIONS AND FORM COEFFICIENTS

Using the approximately 400 barges mentioned in Section 2 as a data base, ratios of principal dimensions were plotted against overall length. Figure 8 shows a fairly good correlation between L/B and L , especially for the smaller barges. One factor contributing to some of the higher L/B values, especially in the neighborhood of $L = 90$ m, may be limitations on breadth imposed by the width of locks or bridges. The width of building berths in Canada is another constraint on barge breadth.

Figures 9 and 10 show L/D and B/D plotted against L . More scatter is evident in these plots, although envelopes of the values can be drawn, as shown in the figures. The effect of L/D on stability is not clear, since $L/D = L/B \times B/D$, and stability increases with smaller L/B but with larger B/D .

The ratio of deadweight to displacement (DWT/Δ) is a measure of a barge's carrying capacity. This will usually be in the range .74 to .84 and depends on the type of cargo carried. Railcar barges, for example, often have more buoyancy than needed to carry a single deck load of cars and tend to have low DWT/Δ ratios, unless other cargo is loaded below deck. A decrease in DWT/Δ should indicate a more lightly loaded barge, hence increased freeboard and greater righting arm (GZ), assuming other parameters remain constant.

Block coefficient (C_b), based on LWL, typically varies between .81 and .92. Allan and Muhlert [54] listed eleven barges with an average block coefficient of .86. Block coefficient can have an influence on stability. Of course, one cannot vary C_b alone; changes must also be made in some other parameters as well. To illustrate the effect of C_b on stability, GZ curves were calculated for:

- a selected barge with $C_b = .86$
- a rectangular block ($C_b = 1.00$) with the same L , B , D , d , and KG as the barge

Figure 11 shows these curves. Righting arms are reduced by the increase in block coefficient, for a hull of the same principal dimensions.

Generally, then, one would expect to find an increase in stability in barges with:

- decreased L/B ,
- increased B/D ,
- decreased DWT/Δ ,
- decreased C_b ,
- decreased d/D (i.e. increased freeboard).

SECTION 5 - BARGE CASUALTIES

Data on barge casualties was drawn mainly from that provided by the Canadian Coast Guard. Since 1975, the Coast Guard has kept a computerized record of any such casualties. A total of 150 barge casualties were reported as having occurred from February 1975 to June 1982. Many of these casualties were not related to stability, e.g. collisions and fires. Table 8 shows the number of casualties by type and by year. The reason for the exceptionally large number of casualties reported for 1981 is not clear; most of the increase appears to be due to groundings. The 1982 data include casualties up to June 7 only.

The 15 incidents judged to be stability related are included in Table 8 under "capsize/stability". This judgment was made after reviewing, for each casualty, the data regarding type of barge, weather, cargo, location, and a brief description of the incident. In several cases, further documentation, such as the master's casualty report, was examined for additional information. These 15 incidents are listed in Table 9. The "statement" in this table is taken from the Coast Guard reports.

It is difficult to draw any conclusions from the data available. Of particular interest would be the vertical centre of gravity (KG) of the barge and cargo before the casualty. This data is normally not available for most barges. From several barge capsizes that were examined in detail by Robert Allan Ltd., it was found that an accurate estimate of KG required many hours of investigation.

Several inconsistencies and inaccuracies are apparent in the reported data. The "Plymouth", on May 3, 1976, is reported to have experienced a calm sea and winds of 1,300 km/h. The location given for the capsize of the "NBF 12" is two miles inland. The name of barge number 12 in Table 9 is given as "Chaland". This vessel was not found in the List of Shipping, perhaps because "chaland" is French for "barge".

While the above examples may be merely annoying or amusing, similar inaccurate or missing data limits the usefulness of casualty reports. The "Millbanke V", for example, is described as empty, carrying zero tons of cargo. Yet the type of casualty is listed as "cargo overboard". In order to attempt to determine a vessel's intact stability, precise knowledge of the amount and distribution of cargo aboard is essential.

Another factor contributing to the scarcity of data may be the reluctance of many seamen to give a full and accurate report of a casualty. One can imagine a variety of reasons for such reluctance: a dislike of paperwork, a desire to defend oneself or fellow seamen, or just lack of time. In several cases it is apparent that the crew simply did not know what happened. The capsize of the "FMC 100" is an example. Despite the full reports made by master and crew, the time, location, and cause of capsize remain a mystery.

From Table 9 it can be seen that stability related casualties occur to a variety of barges and in various circumstances. The list includes deck, tank, rail car, and dump barges. Barge sizes range from 24 to 105 metres in length and from 250 to 3,700 GRT. Corresponding DWT range is estimated at about 450 t to about 7,000 t. Environmental conditions range from clear, calm sea and no wind to a reported 160 km/h (85 knots) storm. Further details for each casualty are presented in Appendix 1.

Two tentative trends may be observed. First, in many of the casualties, taking on water may have been a factor. This appears to have been the case for at least six casualties (numbers 5, 6, 8, 10, 13 and 15 in Table 9) and may have been a factor in the others; at least, no available information rules it out.

Secondly, the barges in the list are generally older vessels. Average age at time of casualty is 15 years. Due to the typically rigorous service of barges, this could be further evidence for the presence of water on board from leakage or local structural failure.

From discussions with those involved in building, operating, and repairing barges, there appears to be a consensus that most, if not all, capsizes involve taking on water. Water might be present in the hull due to leakage, structural failure, or failure to properly secure hatches. Such water might go undetected for a longer period in an unmanned vessel. Reduction in stability would come from both decreased freeboard and free surface effects.

As an example of the effect of water in a barge hull, consider barge number 26 in Table 1. In the loading condition shown in Table 1, intact $GM = 1.61$ m. Now, assuming one compartment has water in it, and treating this as a conventional free surface case (neglecting dynamic effects), barge GM reduces to 1.39 m, a 14 percent reduction in initial stability. Although this simplified treatment neglects the effects of bottom structure and applies only to very small angles of heel, it does show that water in the bilges can significantly reduce stability.

SECTION 6 - STANDARDS OF INTACT STABILITY

6.1 MEASURES OF STABILITY

Virtually all measures of vessel intact stability are based on properties of the righting arm (GZ) curve, Figure 12. A vessel's GZ is known as its statical stability.

GZ values are usually calculated for a vessel in still water. Formerly, the "constant trim" method was most commonly used. This method assumes constant fore-and-aft trim, even though such an assumption violates hydrostatic equilibrium for most vessels. The method has the advantage of simplified calculation. Recently, with the development of computer programs for stability calculations, the method of "constant trimming moment" is being used more often. With this method the vessel is allowed to trim as it heels so as to satisfy the conditions of hydrostatic equilibrium. When discussing GZ curves, one should be aware of which calculation method was used, since differences may be significant, especially if the vessel has a raised forecastle. If such a portion of the vessel immerses when heeled, a large trimming moment may result. Calculations in this report are based on constant trimming moment, unless stated otherwise.

It should be noted that if the ordinates of the GZ curve are multiplied by displacement, the result is a curve of righting moments.

$$\text{Righting moment} = \text{GZ} \times \triangle$$

This is the moment required to heel the vessel to a particular angle θ . Hence two vessels of differing displacements and which had the same righting arm would have different righting moments. This becomes important during considerations of the heeling moments acting on a vessel. If a particular heeling moment is proportional to displacement, then GZ is a proper measure of a vessel's ability to resist that heeling. If, however, a heeling moment does not vary linearly with displacement, then righting moment is the appropriate measure of stability.

For simplicity, the following discussion refers to righting arms.

Metacentric height (GM) has been used to indicate vessel stability, since the 18th century [5]. Its value is the slope of the GZ curve at zero degrees of heel; see Figure 11. However, calculation of GM is relatively simple in that it does not require determination of the full GZ curve. GM can be termed "initial stability", since it is a measure of a vessel's ability to resist heeling moments from the upright condition.

Ozkan [55] suggested using GM as a description of the vessel's stability for a range of heel angles, not just the upright condition. His method, however, requires knowledge of the GZ curve and as such does not offer the simplicity of a true GM criterion.

Various other quantities associated with the GZ curve include:

1. The angle at which GZ is a maximum, θ_m
2. The angle where GZ becomes zero, θ_0 , defining the range of positive stability.
3. The area under the GZ curve (called dynamic or dynamical stability) from $\theta = 0^\circ$ to θ_m . This area is a measure of energy required to heel the vessel to θ_m .

$$e_r = \int_0^{\theta_m} GZ \, d\theta$$

4. The area from $\theta = 0^\circ$ to 30°
5. The area from $\theta = 30^\circ$ to 40°

We have seen that intact stability (GM), statical stability (GZ), and dynamic stability (e_r) are various measures of a vessel's ability to resist heeling. Furthermore, GM and e_r can be viewed as properties of the curve GZ vs. θ .

A still evolving class of measures of stability is based on a probabilistic approach. Examples of such measures include:

1. Probability of a vessel capsizing in a given life span (e.g. 20 years)
2. Probability of capsize for a single voyage
3. Probability of exceeding a certain angle of heel, either in the vessel's life span or in a single voyage.

The means for accurately calculating such probabilities are not yet at hand. Even if they were, there is still the question of what constitutes an acceptable risk level. For example, what would be an acceptably small chance that a vessel would capsize in her life span? One out of ten? One out of one hundred? One out of one thousand? The smaller the risk of capsize, one would presume, the "safer" the vessel. But making a vessel more "stable" often involves penalties, such as increased cost of construction, more severe restrictions on cargo stowage, or higher accelerations (therefore higher risk of damage from shifting cargo). The advantages of a reduced probability of capsize must be weighed against the resulting penalties in other areas.

6.2 NATIONAL CRITERIA

Stability criteria for barges have been established by the United States [56] and Great Britain [57], while Canada has issued an interim standard [1]. Before examining each of these in detail, the general background common to them will be reviewed.

In 1939, Jaako Rahola [59] presented a doctoral thesis on ship stability. Rahola analyzed casualty records for about 30 ships, most of them Baltic coastal vessels, 30 m to 90 m in length. He then proposed a criterion, based on the GZ curve, for sufficient intact stability. His criterion specified, according to [5] and [60]:

1. $GZ \geq 0.14$ m for $\theta = 20$ degrees
2. $GZ \geq 0.20$ m for $\theta = 30$ degrees
3. $GZ \geq 0.20$ m for $\theta = 40$ degrees
4. θ_m (angle for maximum GZ) ≥ 35 degrees
5. $e_r = 0.08$ m rad for $\theta = 0$ to θ_r , where θ_r is the smallest of θ_m , angle of downflooding, angle for cargo shifting, or 40 degrees.

Later the International Maritime Organization (IMO) became concerned with establishing stability criteria for cargo, passenger, and fishing vessels. IMO published criteria [61] and [62] based on Rahola's work. While IMO's criteria are not binding on any nation, the concept of establishing minimum stability standards with a Rahola-type criterion gained formal acceptance.

For cargo ships under 100 m in length, IMO recommends [61]:

1. $GM \geq 0.15$ m at departure
2. $GZ \geq 0.20$ m for $\theta = 30$ degrees
3. $e_r \geq 0.055$ m rad for $\theta = 0$ to 30 degrees
4. $e_r > 0.09$ m rad for $\theta = 0$ to 40 degrees (or to the angle of downflooding, if less than 40 degrees).
5. $\theta_m \geq 25$ degrees, but preferably $\theta_m > 30$ degrees.

Certain allowances are made for ships carrying timber on deck. Thomson and Tøpe [60] discuss the background to IMO's criteria. These criteria are not intended for barges; [60] indicates that the maximum intended B/D is about 2.5.

Let us now examine the various national criteria. An analysis of these criteria follows.

6.2.1 United States

The U.S. Coast Guard [56] uses a two part standard to assess barge stability. The first part, known as the "weather criteria", governs minimum metacentric height by the formula:

$$GM = \frac{P A h}{\Delta \tan \theta},$$

where

$$P = .005 + \left(\frac{L}{14,200}\right)^2 \text{ tons/ft.}^2 \text{ for ocean, coastwise and Great Lakes winter service}$$

$$= .0033 + \left(\frac{L}{14,200}\right)^2 \text{ tons/ft.}^2 \text{ for Great Lakes summer service}$$

L = Length between perpendiculars

A = Projected lateral area in square feet of portion of vessel above waterline

h = Vertical distance in feet from centre of A to centre of underwater lateral area or approximately one half draft point

Δ = Displacement in long tons

θ = Angle of heel to one-half the freeboard to the deck edge or 14 degrees, whichever is less.

This formula applies, incidentally, to all U.S. vessels on international or coastwise voyages (46 CFR 93.07).

The second part, "dynamic stability criteria", establishes minimum dynamic stability up to the angle of maximum righting arm as 15 ft deg (.0798 m rad) for ocean, coastwise, and Great Lakes winter service. The value for Great Lakes summer service is 10 ft deg (.0532 m rad).

The USCG has made an effort to reduce the work involved in applying the criteria. Inclining is not required for most barges. Lightship weight for deck barges may be estimated by the formula:

$$W_{LS} = (.003 + 0.1/L) L \times B \times D,$$

where L, B, and D are in feet and W_{LS} is in long tons. No calculation of dynamic stability is required if the barge's proportions fall within certain limits of B/D and d/D (see Figure 13).

A simplified graphical method is provided for barges outside of these limits but which fall within a second set. Only for barges outside of this second set are full GZ curves required.

The USCG stability criteria further distinguish between different types of barges. Special considerations apply to derrick and hopper barges. Derrick barges are checked for heel under hook load and, if counterballasted, for stability if the hook should suddenly let go. Hopper barges are checked for the effect of water in the hoppers.

In addition to reference [56], several portions of the U.S. Code of Federal Regulations (CFR) also apply to barge stability. The CFR is a codification of the rules made by various departments of the executive branch of the federal government. The rules made by the USCG are what concern us here.

Under the subpart, "Barge Hull Construction Requirements" (46 CFR 151.10), the dynamic stability criteria mentioned above are repeated, with the addition that 5 ft deg (.0266 m rad) is the minimum value for river service.

Barges whose "vertical centre of gravity for cargo is below the deck at side" may have their required transverse stability determined by minimum GM from the formula:

$$GM = kB/f_e$$

$$k = 0.3 \text{ for rivers}$$

$$= 0.4 \text{ for lakes, bays, sounds, and the Great Lakes-summer}$$

$$= 0.5 \text{ for oceans and the Great Lakes-winter}$$

$$B = \text{Beam (feet)}$$

$$f_e = \text{Effective freeboard } (f + f_a) \text{ in feet. This is freeboard to the deck at side } (f) \text{ plus a freeboard augmentation } (f_a) \text{ for those barges with a watertight (structural) trunk. When draft } (d) \text{ is less than } f_e, \text{ it is used in lieu of } f_e. \text{ The freeboard augmentation } (f_a) \text{ may be calculated by the following formula:}$$

$$f_a = 1.25 \left(\frac{1}{L} \right) \left(\frac{2b}{B} - 1 \right) h \text{ or } h,$$

whichever is less where:

$$l = \text{Trunk length (feet)}$$

$$L = \text{Overall length (feet)}$$

$$b = \text{Trunk breadth (feet)}$$

$$h = \text{Trunk height at side (feet)}$$

(46 CFR 151.10-5)

A minimum longitudinal metacentric height (GM_1) is also required by:

$$GM_1 = 0.02 L^2/d$$

where

$$L = \text{Overall length (feet)}$$

$$d = \text{Draft (feet)}$$

(46 CFR 151.10-6)

Several provisions of the CFR apply to special types of barges. For tank barges, the light ship KG may be assumed to be 0.6 D with no inclining test required (46 CFR 31.10-30). Barges carrying grain in bulk fall under 46 CFR 31.10-33 and 46 CFR 93.20. For tanks carried in saddles, 46 CFR 151.10-20 gives structural design requirements.

6.2.2 Great Britain

Like the United States, Great Britain uses a stability standard [57] which considers both heeling under a wind load and dynamic stability. Wind pressure is assumed to be 75 kg/m² and applied to the lateral windage area; resulting heel should not immerse more than half the freeboard.

The dynamic stability criteria require areas under the righting arm curve of:

1. 0.08 m rad up to the angle of maximum GZ, and
2. 0.03 m rad from 30 degrees to 40 degrees, or to the angle of down flooding if this is less than 40 degrees.

Consideration of the effects of cargo water absorption and of icing is required where appropriate. No allowance is made for the buoyancy of deck cargo.

These criteria are more stringent than those of the USCG, particularly in regard to requiring .03 m rad of dynamic stability between 30° and 40°.

6.2.3 Canada

The Canadian Interim Standard (see Appendix 1) applies to cargo barges which are required to be assigned loadlines and constructed after September 1, 1977 [1]. The Standard does not apply to crane, derrick, or hopper barges. It requires:

1. that the barge be inclined (although generally the CCG will accept calculated KG);
2. that the minimum dynamic stability, up to the angle of maximum GZ, be 0.08 metre radians; and
3. that the minimum longitudinal stability be

$$GM_1 = .02L^2/d \text{ metres}$$

where

$$\begin{aligned} L &= \text{overall length in metres} \\ d &= \text{draft in metres} \end{aligned}$$

For barges whose vertical centre of gravity of cargo is below the deck at side, stability may be determined by the following formula:

$$\text{Minimum GM} = kB/f_e$$

where

- k = .15
- B = beam in metres
- f_e = effective freeboard (f + f_a) in metres
 - where
 - f = freeboard to the deck at side in metres
 - f_a = additional freeboard allowance for barges having a structural watertight trunk
 - f_a = $1.25 \frac{hl}{L} \left(\frac{2b}{B} - 1 \right)$ or h, whichever is less
 - l = length of trunk in metres
 - L = overall length of barge in metres
 - b = breadth of trunk in metres
 - h = trunk height at side in metres

It may be noted that the GM₁ requirement is identical to that in the U.S. regulations. the GM requirement based on freeboard is also of the same form as the U.S. regulations, except that in the Canadian Standard, k = .15 and GM is in metres. The equivalent for a metric GM under the U.S. regulations is k = .1524 (for ocean and coastwise service).

The Canadian standard makes no differentiation for areas of service, but since it applies only to load line barges, ocean or coastwise service may be inferred. Hence the U.S. and Canadian standards are virtually identical.

6.3 EVALUATION OF NATIONAL CRITERIA

The criteria examined above fall into two broad types: those which specify a minimum initial stability (GM or GM_1), and those which specify a minimum dynamic stability (e_r). The first type may be further divided into weather, GM -freeboard, and GM_1 criteria.

The GM criteria, however defined, can set standards for only the initial stability of a vessel, that is, its ability to resist heeling while in an upright condition. As a safeguard against capsizing, which involves large angles of heel, a GM criterion is effective only to the extent that initial stability is proportional to overall stability. Figure 14 shows the righting arm curves for two vessels. Both have the same GM but widely differing e_r . Therefore it is dangerous to rely on GM alone as a stability criterion, unless the range of vessels is so restricted that GM is also a good measure of dynamic stability.

To examine the relationship between initial and dynamic stability for barges, Figure 15 was prepared. It shows, for the 30 selected Robert Allan Ltd. designs, dynamic stability vs. initial stability. The scatter in the points indicates that GM is not precisely related to e_r . Thus GM alone would not be a suitable criterion for barge stability.

6.3.1 Weather Criteria

The USCG weather criterion uses a limiting heel angle of 14 degrees or immersion of half the freeboard, whichever is less. For almost all barges of normal proportions, the half freeboard condition will take precedence. This criterion has a good degree of rationality; there is a notable relationship between terms in the criterion's equation and forces in the real world. The quantity P may be thought of as wind pressure, and PAH as the heeling moment due to wind. Restoring moment (for small angles of heel) is then $GM \Delta \tan \theta$. Setting heeling moment equal to restoring moment:

$$PAH = GM \Delta \tan \theta$$

which leads to

$$GM = \frac{PAH}{\Delta \tan \theta}$$

An assumption implicit in limiting heel to half the freeboard is that there is then a reserve of stability to resist heeling from forces other than wind, such as waves.

Great Britain's weather criterion is similar, the principle difference being wind pressure is specified as 75 kg/m^2 . For the USCG [56], wind pressure varies with length (L):

L, m	P, kg/m^2
0	54.7
50	56.1
100	60.5
150	67.8
200	78.0

Thus the British weather criterion is more severe than that of the USCG for barges under 186 m in length.

One rationale for the USCG's increase in wind pressure with length is that wind speed close to the sea's surface is usually less than the free stream wind speed. Smaller vessels would be closer to the surface and experience reduced wind speed and pressure. However, under this reasoning it would seem more appropriate to have wind pressure vary with height above sea level, rather than with length.

6.3.2 GM - Freeboard Criteria

An analysis of the GM - freeboard criteria appears in Appendix 3. Results are shown in Figure 16. This analysis considered the Canadian criteria with $k = 0.15$, but the results would need only minor adjustment to reflect the U.S. criteria with $k = 0.1524$.

Figure 16 represents proportions (beam/draft ratio and draft/depth ratio) and depth for barges which just meet the criteria. Assumptions were made to reflect the most conservative case. No freeboard credit for a trunk was used, and KG for the barge and cargo was taken at deck level. This can be thought of as maximum KG, since the criteria apply only to a barge with cargo vertical centre of gravity below the main deck. For each value of breadth/depth, B/D, any barge with d/D below the curve is "safe", that is, available GM would be greater than minimum required GM. Thus this criterion reduces to essentially a freeboard criterion. Figure 16 can be viewed as the minimum required freeboard for a given D and B/D.

It is therefore appropriate to compare this criterion with freeboards as determined by the Load Line Regulations [63]. Accordingly, freeboards and draft/depth ratios were calculated for barges with various depths. Since [63] is based on length, values of L/D were assumed to generate the family of curves shown as dashed lines of Figure 16. These curves assume no trunk or superstructure, no sheer, and a block coefficient of 0.86.

The curve for L/D = 6 represents the minimum L/D according to the longitudinal stability criterion, as shown in the following subsection.

For a barge required to meet both the GM-freeboard criterion and the Load Line Regulations, Figure 16 indicates that smaller barges are governed by the former (GM-freeboard) criterion. Larger barges tend to be governed by the Load Line Regulations. Furthermore, for barges of the same proportions (i.e. B/D and L/D) but differing size, and GM-freeboard criterion allows greater draft/depth ratios for larger barges. The Load Line Regulations, however, show the opposite trend. Larger barges require slightly reduced draft/depth ratios.

As an example, consider barges 22 and 23 from Table 1. The application of the two criteria (GM-freeboard and Load Line) to each of these barges results in the following:

BARGE NO.	D,m	B/D	L/D	MAXIMUM d/D	
				GM-FBD	LOAD LINE
22	6.10	3.10	13.1	0.836	0.811
23	4.88	2.87	13.9	0.762	0.808

Barge 22 is governed by the Load Line regulations, with maximum d/D = 0.811. For barge 23, on the other hand, the GM-freeboard criterion governs, with maximum d/D = 0.762.

6.3.3 Longitudinal Stability

Both the U.S. and Canadian criteria include a minimum $GM_1 = .02 L^2/d$. This standard may be represented as maximum allowable KG/D vs. L/D (Figure 17). Appendix 4 gives the details for the development of this figure. Also plotted on Figure 17 are points for the selected example barges.

The rationale behind this requirement is not explicitly stated. Presumably the intent is to prevent a barge from tripping end over end, but no such occurrences are known to the writer.

6.3.4 Static and Dynamic Stability

A vessel's curve of righting arms has been an accepted measure of intact stability since Rahola [59]. Stability requirements based on Rahola's work are applied to a variety of vessel types, including passenger, cargo, and fishing vessels. Following a number of casualties involving offshore supply vessels in the Gulf of Mexico, Rahola-type criteria were implemented for this class of ship [64], [65] and [32]. Casualties subsequently decreased.

This type of criterion, however, is open to several criticisms. Among them are:

1. Rahola's work was based on a statistical sample of vessels. The resulting criteria were an attempt to retrospectively distinguish between vessels which capsized and those which did not. Thus, for each part of the criteria, the relationship to physical forces is undefined. The predictive value of such a criterion is therefore questionable.
2. These criteria have been applied to vessels whose size, type, and intended service were different from those in Rahola's sample. As stated by Henrickson [66],

"...the tendency has commonly been to add onto existing, successful criteria and to stretch their limits to cover additional vessel types or new forms. Unfortunately, this method has led to applications of statistically derived standards such as Rahola's to vessels well outside their intended range."
3. Usually the requirements are based on righting arms calculated assuming constant trim, rather than constant trimming moment. Sometimes which method to use is unspecified.
4. The criteria concern the curve of righting arms, not that of righting moments. As mentioned above, righting moment = righting arm x displacement. This would be acceptable if all heeling moments were shown to be proportional to displacement, but such is not the case. Wind heeling moments, for example, are proportional to exposed area rather than displacement.
5. The effect of other requirements which influence stability, such as the Load Line rules, is not explicitly stated. In the present case, barge stability became subject to national regulation only after 1966, when the International Load Line Convention recommended a 25% reduction in freeboard for qualifying barges. Should the Load Line rules be again changed, what affect would this have on existing requirements for barge stability?

6. The allowable probability of capsize is undefined. Safety factors are implicit in the regulations, but not stated explicitly. This presents two difficulties. First, there is no provision for a reliable measure of the effectiveness of the standard, whether it is too liberal (too many casualties), or overly conservative (unnecessary restrictions on operation). Second, others who wish to adopt the standard in conjunction with a different, but known, probability of capsize are unable to make accurate adjustments.

Let us now consider the specific regulations of barge dynamic stability reviewed above.

All three national criteria specify a minimum e_r of .08 m rad up to θ_m , the angle of GZ_{max} . The implicit assumption is that if a heeling moment is strong enough to push the barge to this angle, then it will be greater than any righting moment the barge can offer past this angle, and the barge will capsize. This assumption is valid for most heeling moments and is questionable only for those such as wind gusts which, by their transient nature, may fall to a small value at the time the barge reaches θ_m .

To examine how well barges in practice would meet the .08 m rad requirement, values for GZ and e_r were calculated for each of the 30 example barges from Table 1. Figure 18 shows the resulting values for e_r . Notable from Figure 18 is the large number of barges which fail to meet the .08 m rad minimum. Two observations are relevant here:

1. The proportions of various barge types in the sample are not those of the Canadian fleet. The fleet, for example, contains a far greater percentage of chip barges than the sample, and a lower percentage of log barges. Most probably, the portion of the fleet which would not meet the standard is greater than that indicated by Figure 18.
2. The U.S. regulations and the Canadian Interim Standard apply only to barges requiring Load Line assignment. Barges plying the waters of Puget Sound, inside Vancouver Island, and of the Inside Passage to Alaska are exempt from Load Line requirements [63]. This includes several of the barges in Figure 18. Those barges which commonly make Load Line voyages are noted on the figure. The British regulations make no reference to Load Line assignment.

Another point of interest from Figure 18 is that barges appear to be roughly grouped according to type.

The log barges present a particular case. For these vessels, which self-unload by unsymmetrical ballasting, too much stability can mean they are unable to discharge their cargo.

The crane operators who load these vessels are highly skilled personnel. An executive of one of the major barge operating companies described how the crane operators learn to "feel" the stability characteristics (perhaps the roll period) of a log barge. Perched in a cab high atop the vessel, the operator senses by a "seat of the pants" method when the barge has sufficient stability to make the voyage safely, but not so much that she will fail to dump her load properly. This "feel", or tacit knowledge, is gained by experience. For each new barge, the operators undergo a learning period through trial-and-error loading. Several instances of barges being unable to discharge logs have occurred during initial operations with new barges. However, too little stability can also be a problem with log barges. One such barge twice discharged its cargo inadvertently.

The British standard, like Rahola's criterion, further specifies a minimal e_r value of .03 m rad for between 30 and 40 degrees of heel. The rationale for this requirement is not apparent.

The stability characteristics of most North American barges are such that it would be extremely difficult for them to meet this requirement. See, for example, the barge GZ curves in Figure 3. The broad beam and shallow depth of barge hulls results in a high GM but low range of positive stability.

It may well be that a barge cannot meet this requirement, yet has sufficient e_r before 30 degrees so that safety against capsize is adequate. The work then required to heel such a barge to 30 degrees would be large enough to make attaining such an angle of heel sufficiently unlikely. Possibly this requirement is simply adapted from the earlier Rahola or IMO guidelines, even though they were intended for vessels of quite different "typical" proportions.

The general concept of specifying specific angles of heel in dynamic stability criteria is questionable. The work done to heel a vessel from upright to a certain angle θ is:

$$\text{heeling work} = \int_0^{\theta} GZ \, d\theta$$

or the area under the righting moment curve. Those forces which tend to capsize a vessel, such as waves, wind, or water on deck, act as heeling moments of a certain magnitude. The resulting angle of heel a vessel will take is given by the righting moment and heeling moment curves; it is the angle where the area under the heeling moment curve equals the heeling work. This angle might be 10° for one vessel and 30° for another, yet both may be considered safe from capsize in these conditions.

Figure 19 shows the righting moment curves for two vessels. Superimposed on the graph is a wind heeling moment curve. Vessel A would respond to this heeling moment by heeling to 10°. At this point, the area under the righting moment curve equals that under the heeling moment curve. Vessel B would heel to 30 degrees. Both vessels would survive this particular heeling moment, yet vessel A would fail to meet the British or IMO criteria. Is this vessel demonstrably less safe than Vessel B?

Criteria which include specific angles of heel are appropriate only if those angles are operationally significant. For example, if flooding occurs at a certain angle, then the vessel should be sufficiently stable to avoid reaching this angle. Other than similar operational concerns, the reasons for specifying certain angles of heel are unclear. What is so magical about 30 degrees that a certain minimal GZ or e_r is required there?

Of the three national criteria reviewed above, only the U.S. regulations mention the possible buoyant effects of deck cargo. In the section on "background", Reference [56] refers to "timber carrying barges which enjoyed a dynamic stability assist from their deck cargo." Page 2-1 of the regulations states:

"For barges that are "special cases" (i.e. lumber barges, etc.) these basic principles shall be used as they apply to an individual case."

One example is the case of log barges, which commonly load logs on deck so that the logs extend out past the sides of the barge. If the barge heels to a point where the overhanging logs immerse, the buoyancy of the logs creates an additional righting moment.

The benefits to stability of buoyant cargoes secured on deck are also clearly recognized by IMO [61]. Neither the British nor the Canadian regulations, as written, take this factor into account.

6.3.5 Owner's Stability Criteria

Some barge owners set their own standards to assure safety in barge operations. Many chip scows have painted steel plates welded to the four quarters of the barge hull. The lower edge of each plate defines minimum freeboard for voyages to outside waters such as the west coast of Vancouver Island. The upper edge of each plate defines freeboard for the sheltered waters of Georgia Strait. Other owner-issued guidelines set minimum freeboards for winter and summer operation. Additional requirements include limits on trim and list. Typically, chip scows are required to have at least 280 mm aft trim (for stable course keeping) and a maximum list of 50 mm.

Experience plays a major role in the development of judging when a barge is "safe". Owners have learned that loading bulk cargoes in high peaks leads to decreased stability. Efforts are made to avoid pockets where pools of water may accumulate. Tugboat skippers, while perhaps not conversant with the higher mathematics of stability theory, often have decades of operating experience from which to judge the safety of a tow.

For large barges carrying heavy loads offshore, a naval architect is often consulted to evaluate stability. In such operations, the severe consequences of capsize warrant all reasonable efforts by the owner to insure adequate stability. Too much stability can also be a problem in these cases. An overly stiff barge can result in severe motions and high stress on cargoes and restraining devices.

SECTION 7 - CONCLUSIONS

1. A desirable stability criterion would set a maximum limit for the probability of capsize, given vessel particulars, environmental conditions, and time span considered.
2. At present there is no reliable mathematical method to predict such a probability, nor is there any standard for an acceptable level of risk.
3. Data for statistically describing sea conditions are available for the North Atlantic region. Other ocean areas are not yet statistically well defined, although work towards this end is in progress.
4. Roll damping is an important factor in capsize safety. Damping coefficients appear to be nonlinear with roll angle.
5. The behaviour of water on deck is an important factor in barge capsizing.
6. The quantity, nature, and stowage of deck cargo has a significant effect on capsize safety.
7. Seamanship (selection of heading and speed) appears to have a significant effect on the motions experienced by a towed barge.
8. Several capsize mechanisms have been identified for cargo vessels. These include parametric resonance in a following or quartering sea, pure loss of righting moment on a wave crest, and the accumulation of water on deck.
9. The reported incidence of capsize among Canadian barges is low. In a recent seven-year period, 15 capsizes were reported out of a fleet of about 850 barges.
10. The consequences of a barge capsize are often less severe than those of a ship. For the above 15 capsizes, two deaths and four injuries were reported. Whether these deaths and injuries were caused by inadequate stability is unknown. No other loss of life or injury associated with Canadian barge capsizes is known. Although capsizing usually results in loss of cargo, often the barge is towed to port and re-righted.
11. Barge capsize reports compiled by the Ministry of Transport usually lack significant data such as barge beam, depth, draft, and the amount and vertical centre of gravity of cargo aboard.
12. Currently used barge stability criteria are based on wind heeling moment, minimum GM, and minimum dynamic stability.

13. Required minimum GM alone is not sufficient for a capsize safety criterion, unless its application is limited to a certain class of vessels. The limitation should be such that for all vessels in the class, GM is proportional to dynamic stability.
14. The current Canadian Interim Standard would impose significant restrictions on the cargo carrying ability of some barges.
15. Major barge operators utilize knowledge gained from experience to regulate barge safety. This knowledge may be formally explicit or tacit.
16. When large or unusual loads are to be carried offshore by barge, a naval architect is usually consulted to provide guidance regarding intact stability.

SECTION 8 - RECOMMENDATIONS

1. Further consideration should be given to the need at this time for a Canadian barge intact stability criterion. Records indicate that the losses due to stability-related barge casualties have been small. Of those casualties that do occur, the large majority involve non-Load Line voyages and the provisions of the Canadian Interim Standard (or of the USCG criteria) would not apply in any case. The disadvantages of over-early implementation of such criteria include:
 - a. Possibly unnecessary limitations on barge cargo carrying ability, with consequent loss in fleet utilization.
 - b. The risk that barge owners, operators, and tugboat masters will rely more on such criteria and less on their own judgment of barge safety. This judgment can include more factors than any current criterion, such as knowledge of local weather conditions, characteristics of particular barges, anticipated voyage length, proximity of shelter during the voyage, etc.
2. If an intact stability criterion is deemed desirable, consideration should be given to its inherent degree of complexity. Complexity may be a necessary condition for making the criterion both complete (to cover all significant aspects of stability) and flexible (to allow for optimum loading of barges). The goal here is to have barge operations be both safe and efficient.

For operating personnel (barge loading supervisor or tug master), however, a criterion should be easy to apply. Too much complexity might mean the personnel are unable to properly use the criterion or are unwilling to expend the time and effort needed.

One approach is to have a "two level" criterion. One level would be for naval architects and others engaged in design and analysis. A second level would provide simplified guidelines for use by operating personnel on a routine basis. This second level would be a subset of the first; that is, any barge which meets the second level criterion would also meet the first level. Desirable qualities of each level include:

First Level Criterion

- a. It should be rational, i.e., based on an understanding of the physical phenomena involved. Quantities and relationships used in the criterion should correspond to quantities and relationships in the physical world.

- b. Limitations and assumptions behind the criterion should be clearly stated and available to interested parties. Limitations might include type and size of vessel, nature of service and type of cargo. Assumptions might cover maximum steady wind strength, strength and duration of gusts, and sea state. Neither of these lists is exhaustive. The purpose behind stating such limitations and assumptions is to more easily identify and account for those cases which fall outside of the presumed coverage area.

- c. The criterion should be periodically evaluated. Minimum acceptable probabilities of capsize should be established. Evaluation should determine whether the criteria are too severe or liberal, cover an appropriate range of vessels, cargoes, and services, and are in accord with both successful operating experience and casualties.

Procedures for collecting data on casualties are already in place, although the scope of data collected could be expanded. Such data, to be of use in stability evaluation, should include vessel dimensions, cargo vertical center of gravity, and details regarding most recent sounding of bilges and tanks.

- d. The various factors known to significantly influence capsize behaviour should be accounted for. These include not only initial stability and righting moment, but also the effects of water on deck, water in the bilges, deck cargo, and roll damping.
- e. The various modes of capsize should each be guarded against. These include $GM < 0$, loss of righting moment on a wave crest, resonant rolling, and heeling moment from water on deck and in the hull. An example of a criterion to meet this requirement is given by Odabasi [38].
- f. The criterion should not require greater stability than has already proven adequate from satisfactory operating experience.

Second Level Criterion

- a. Scope of application should be clearly stated. Any limits as to barge type or size, nature of cargo, stowage arrangements, area of operation, time of year, etc. should be set forth.
- b. Relevant quantities should be readily observable. Examples include barge draft and load height. Quantities such as roll gyradius do not meet this requirement; if needed, such quantities should be deducible from those that can be easily measured.

c. The procedure for applying the criterion should take little time.

In short, it should be simple, easy, and quick to use. An example of such a criterion is the current practice of welding loading plates to each quarter of chip barges, to show minimum permitted freeboard.

3. Special consideration should be given to barge voyages where the consequences of capsize would be severe. Examples include carriage of hazardous cargoes or of especially valuable cargoes. For such voyages, the risk involved should be determined to be acceptable before the voyage proceeds.
4. Areas in need of further investigation include:
 - a. The effect of towline forces on barge stability.
 - b. The effect of unintended water in the barge or her cargo.
 - c. The damping coefficients of barges at large angles of roll.
 - d. A wider survey of the intact stability of barges currently operating, including determination of righting moment curves. In determining these curves, the errors involved in the approximation process used in this study (see Figure 1) should be reduced. A sample of barges should be assembled with stability characteristics which are statistically correlated to the Canadian barge fleet.
 - e. The effects of shipping water on deck, for various barge types and cargo configurations.
 - f. The desirability of calculating righting moments in waves vs. still water.
 - g. The effects of seamanship on barge capsize safety.
 - h. The effects of large values of stability parameters on barges. For instance, do accelerations increase to an undesirable level? There is some indication that barges can be very seaworthy. The "Hudson Handler", a 29 m long self-propelled submarine tender, has a reputation for easy motions in a seaway, despite a length/beam ratio of 2.4 and a beam/draft ratio of about 20. On the "Seaspan Rigger", a 120 m long log barge, two men who were aboard to conduct instrumentation tests were quite comfortable, unaware that those aboard the towing vessel were being thrown about in the midst of a gale.

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FIGURES AND TABLES

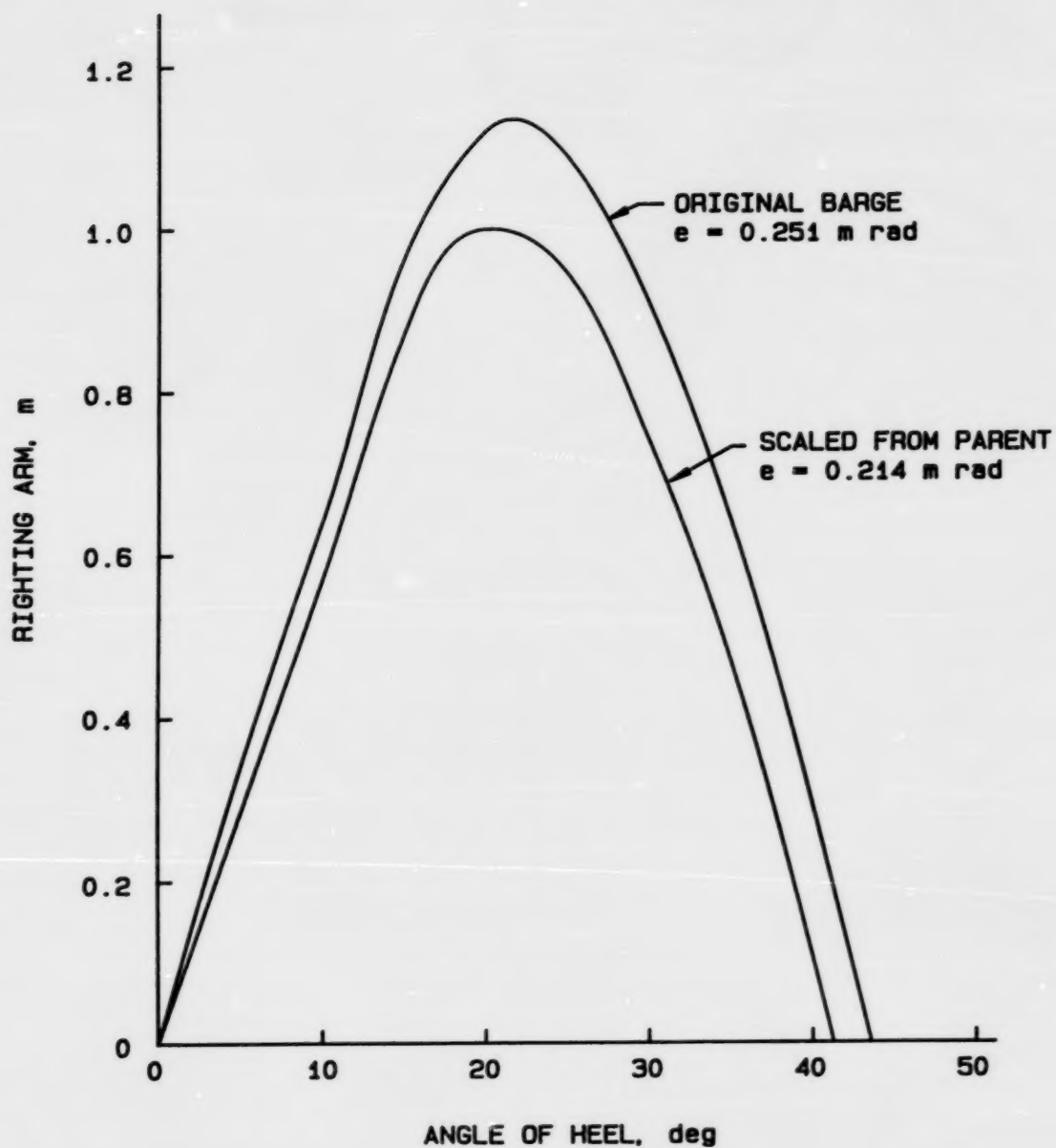


FIG. 1. RIGHTING ARMS FOR BARGE
AND SCALED VERSION

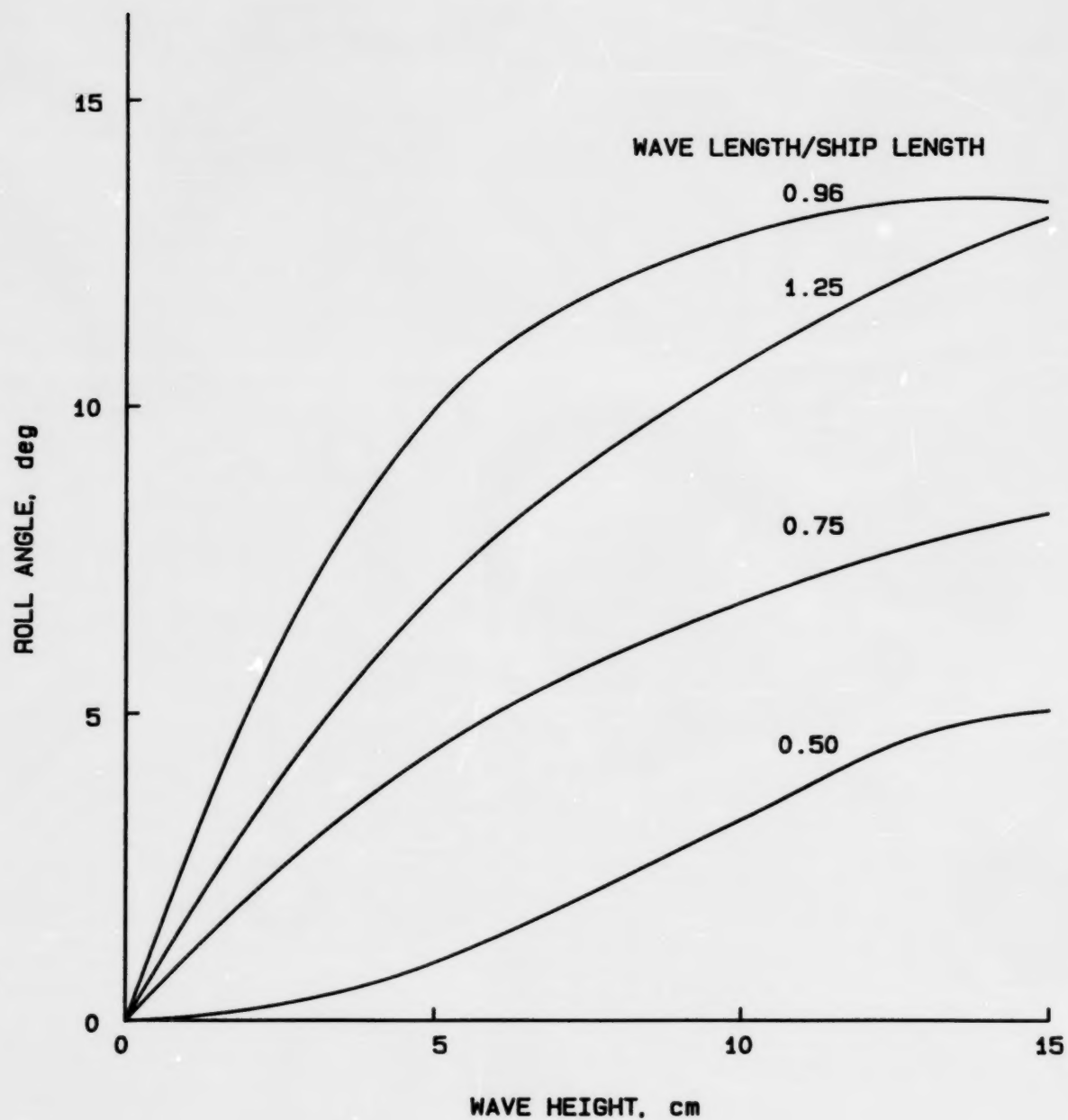


FIG. 2. ROLL ANGLE vs. WAVE HEIGHT
FOR TANKER MODEL, from [11]

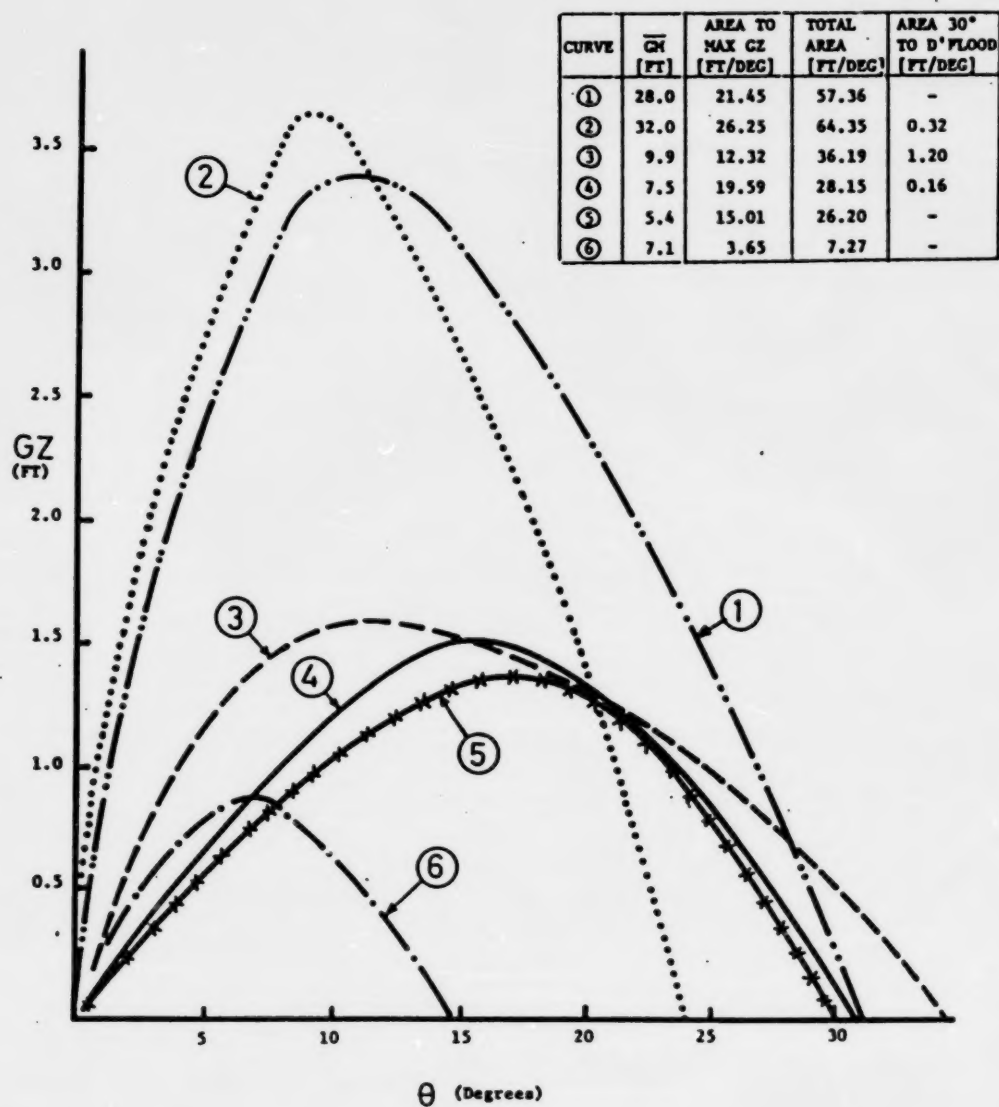


FIG. 3. RIGHTING ARM CURVES FOR SIX BARGES, from [2]



FIG. 4. SELF-LOADING AND SELF-DISCHARGING LOG BARGE

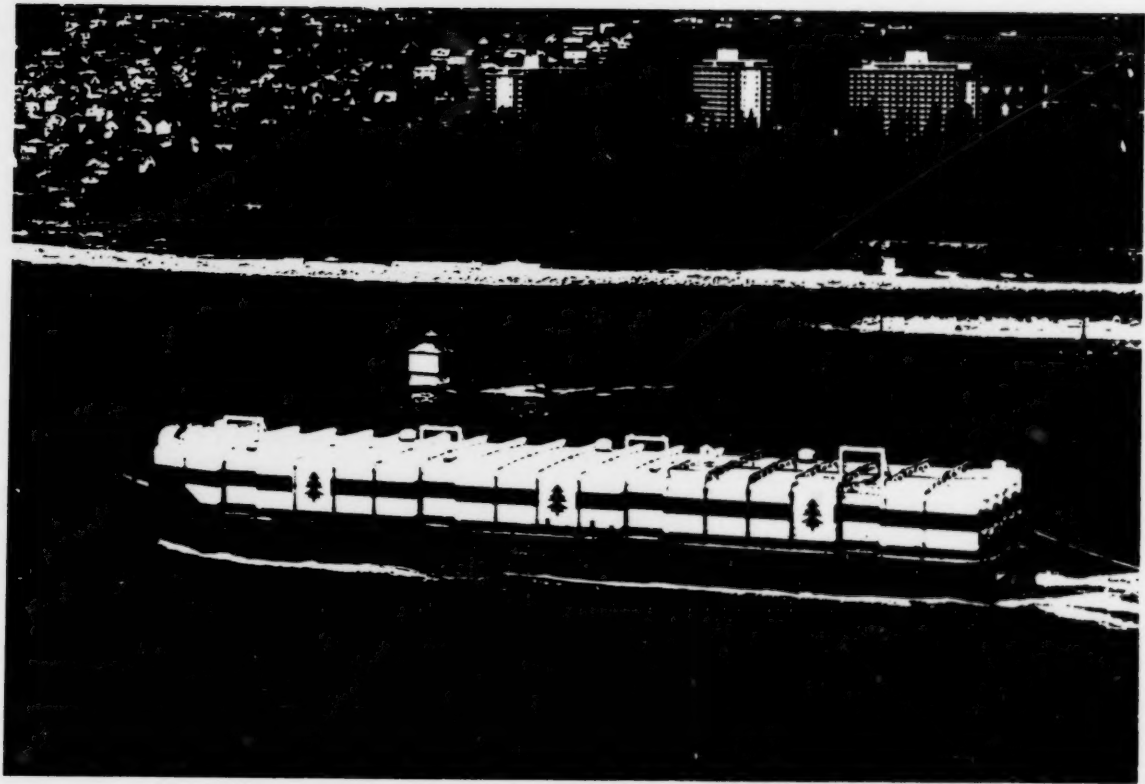


FIG. 5. COVERED BARGE

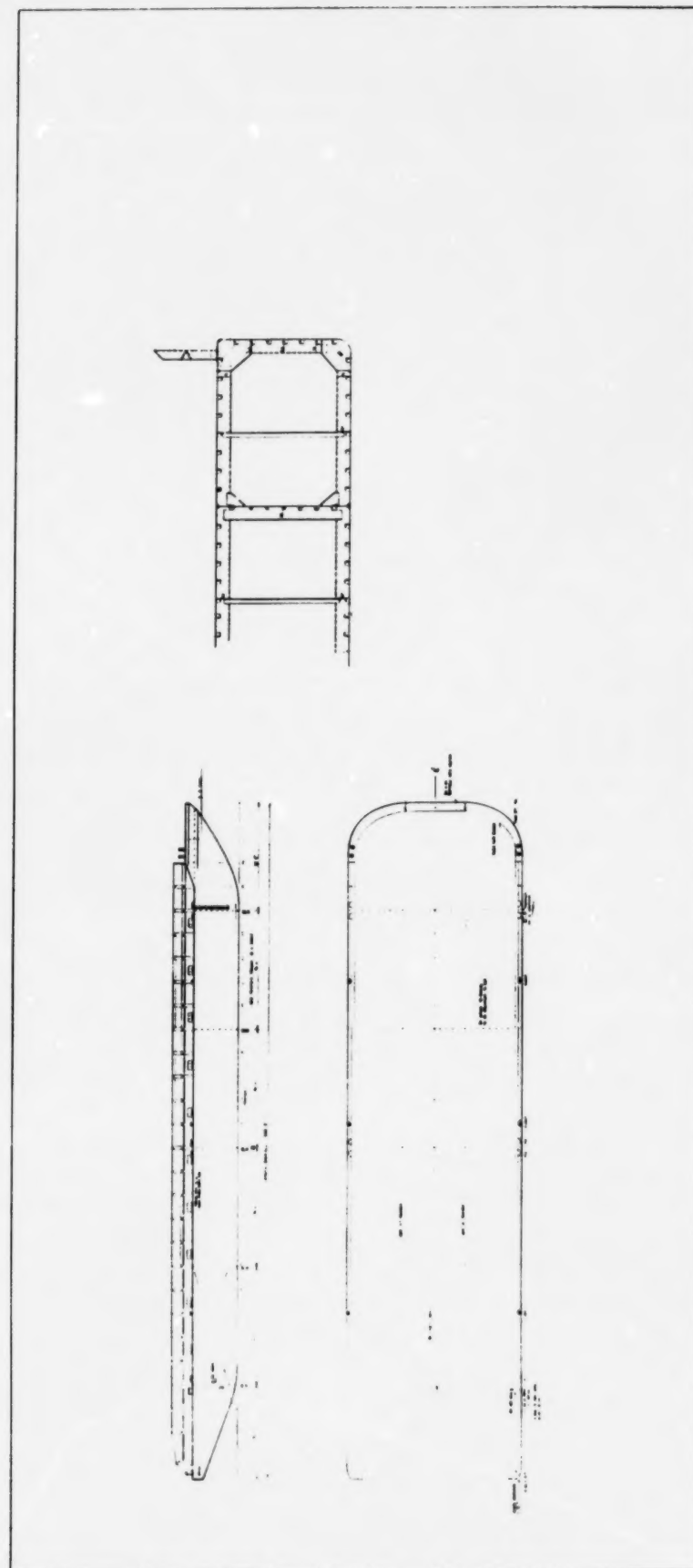


FIG. 6. DECK CARGO BARGE

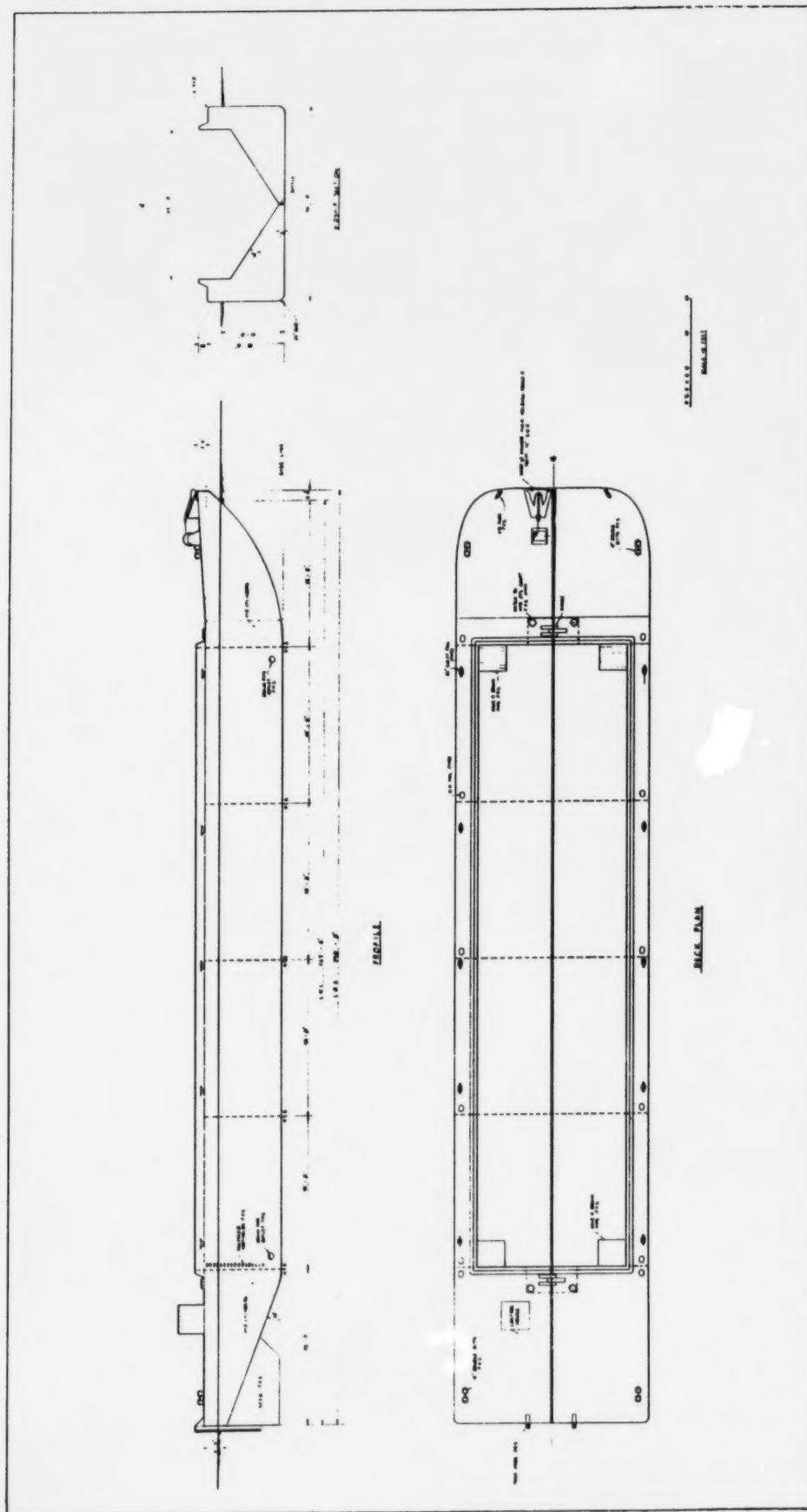


FIG. 7. DUMP SCOW

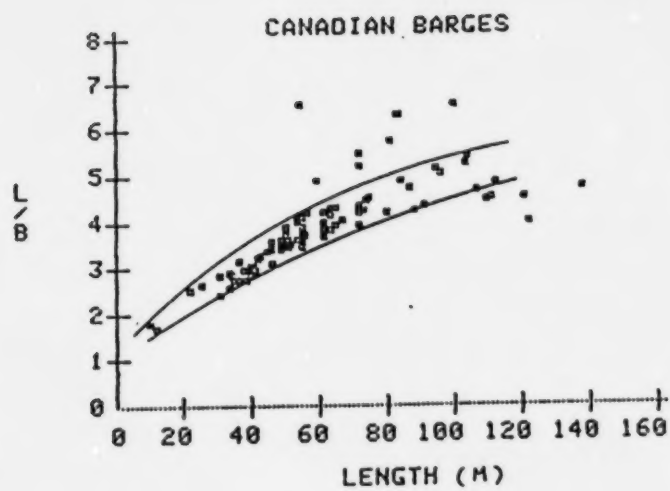


FIG. 8. LENGTH/BEAM RATIO VS. LENGTH

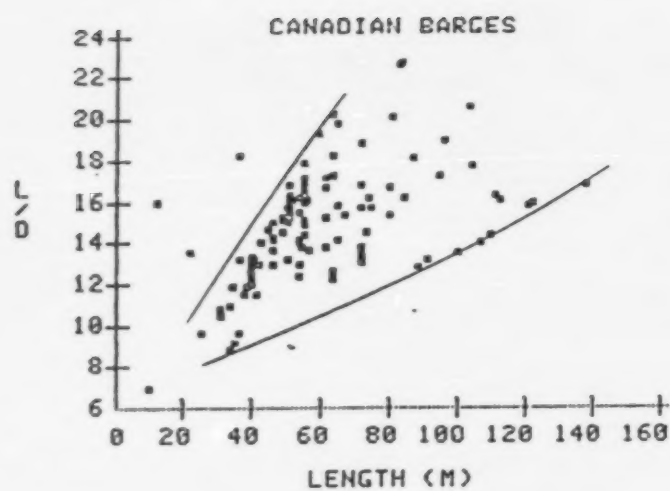


FIG. 9. LENGTH/DEPTH RATIO VS. LENGTH

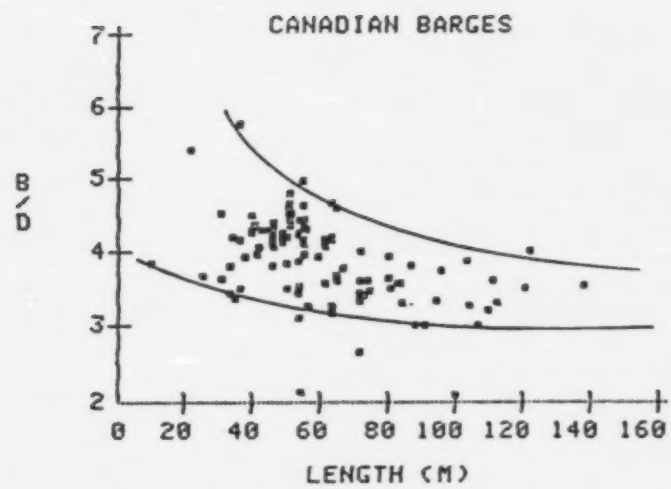


FIG. 10. BREADTH/DEPTH RATIO VS. LENGTH

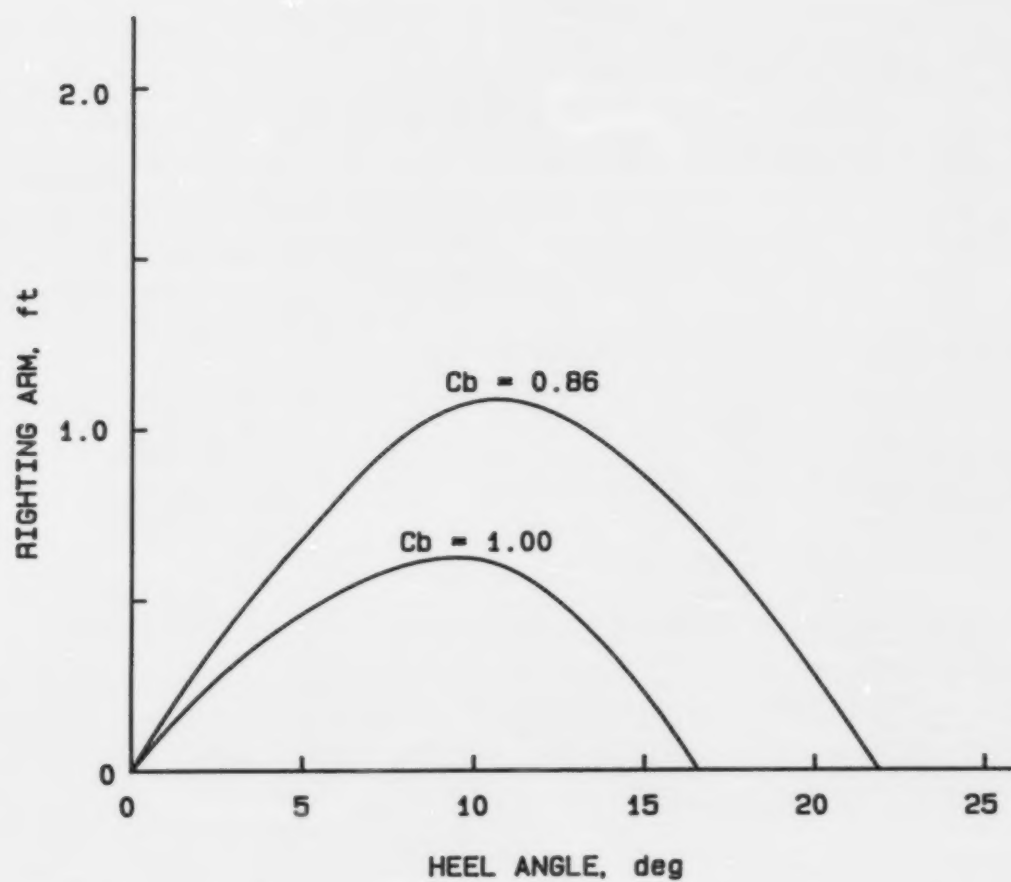


FIG. 11. RIGHTING ARMS FOR DIFFERING
BLOCK COEFFICIENTS

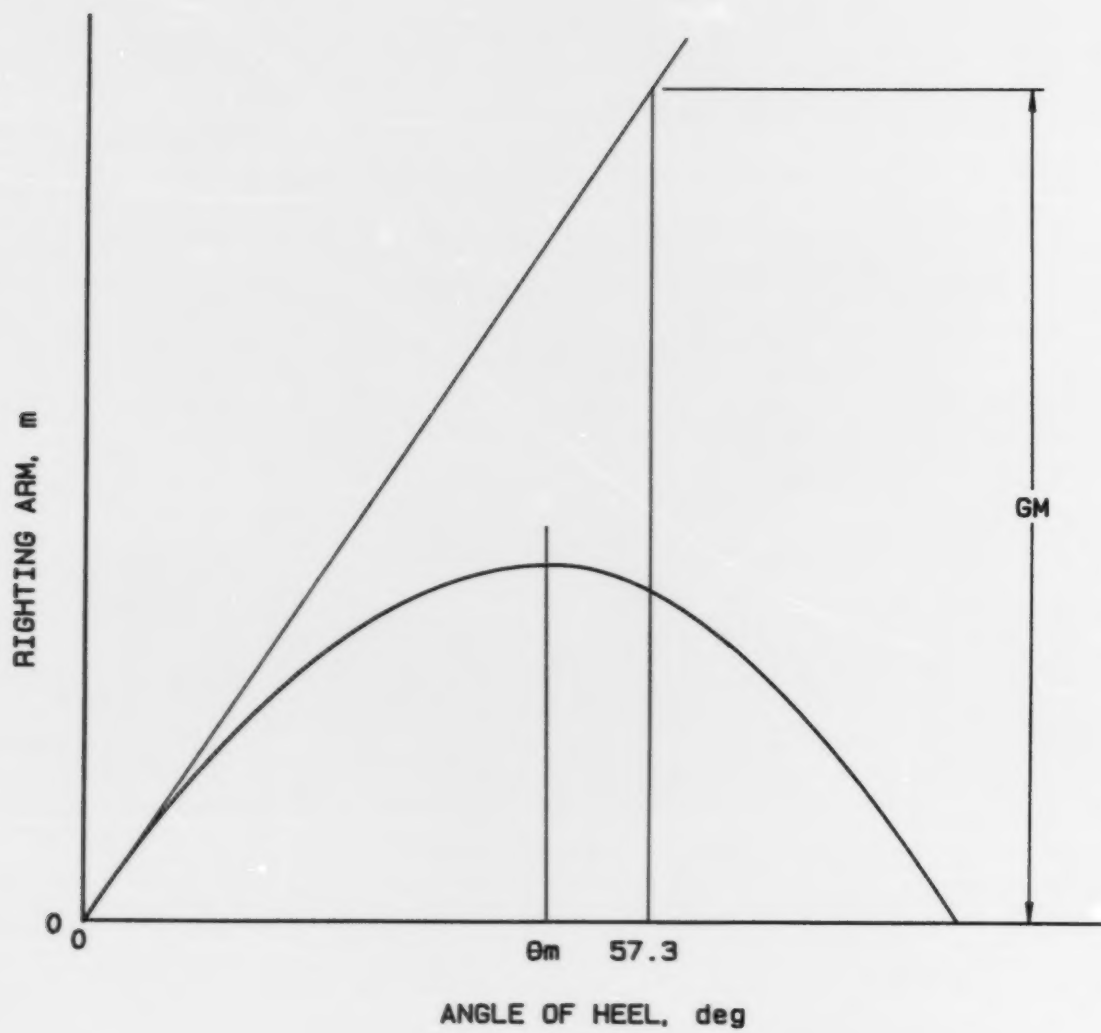


FIG. 12. RIGHTING ARM CURVE

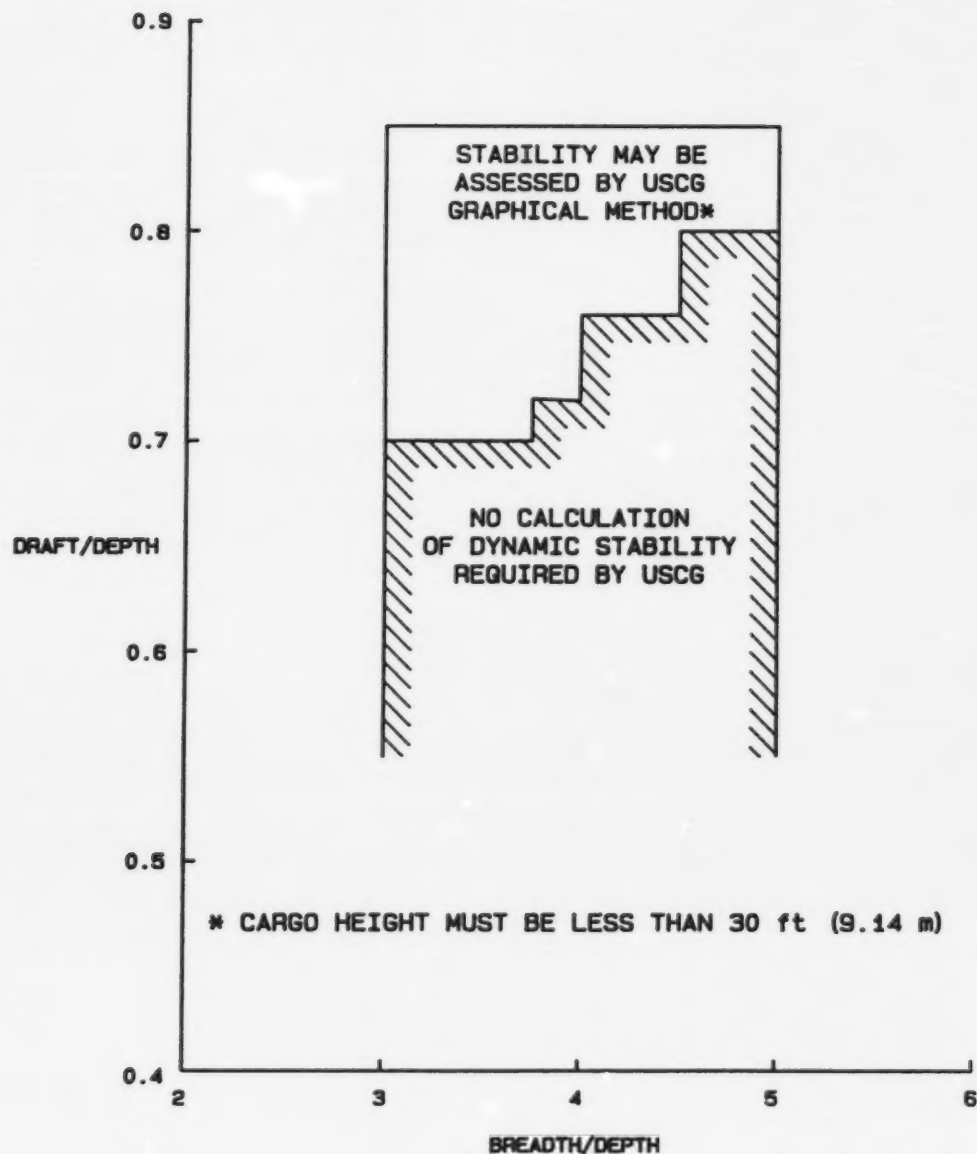


FIG. 13. LIMITS FOR REQUIRED CALCULATION OF STABILITY BY USCG [56]

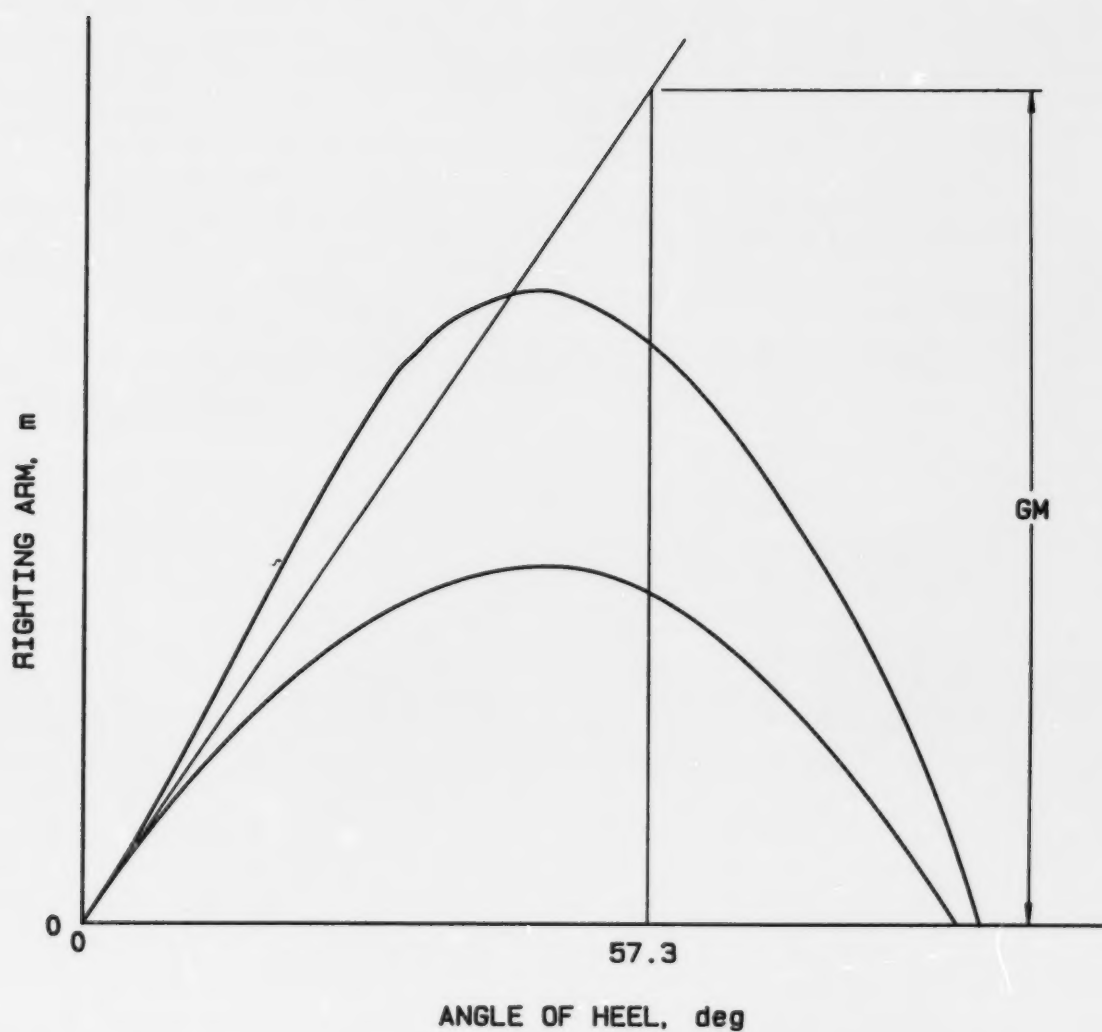


FIG. 14. RIGHTING ARM CURVES
FOR TWO VESSELS WITH SAME GM

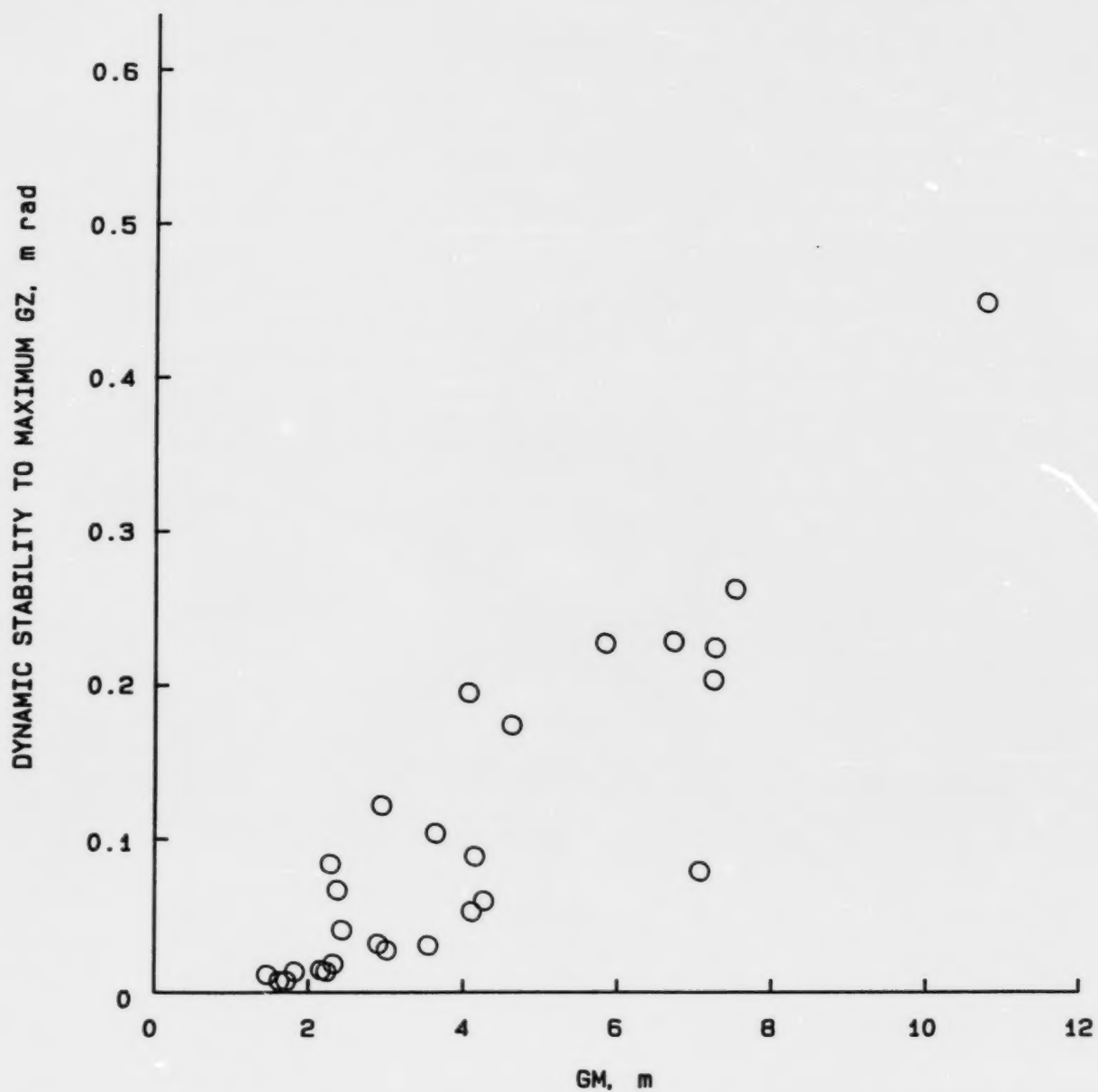


FIG. 15. DYNAMIC STABILITY vs. INITIAL STABILITY

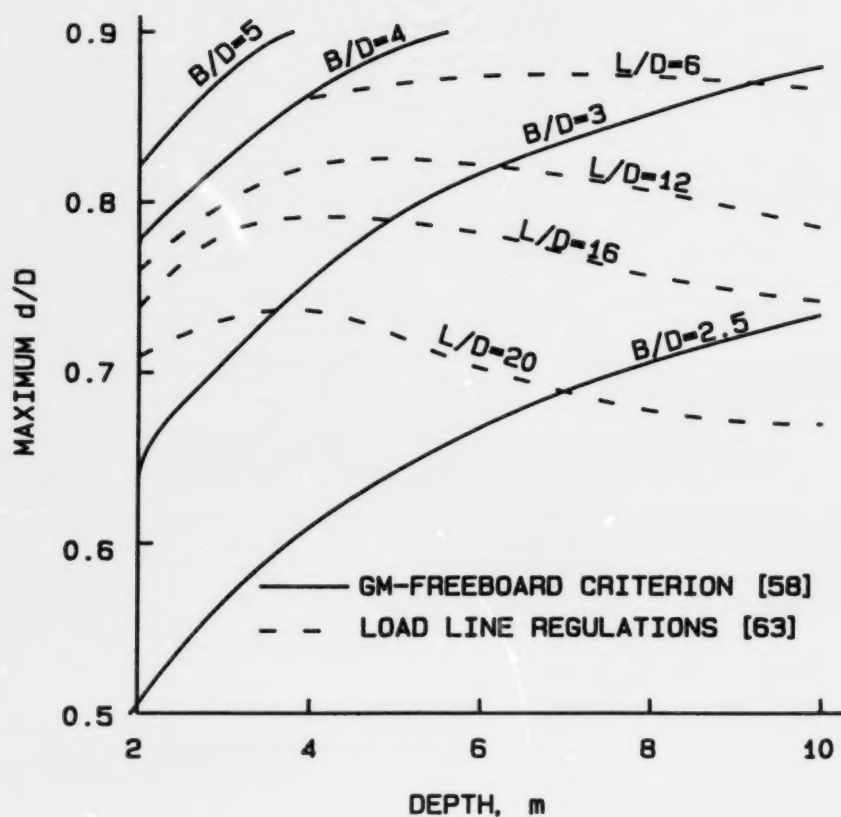


FIG. 16. GM-FREEBOARD CRITERION AND
LOAD LINE REGULATIONS

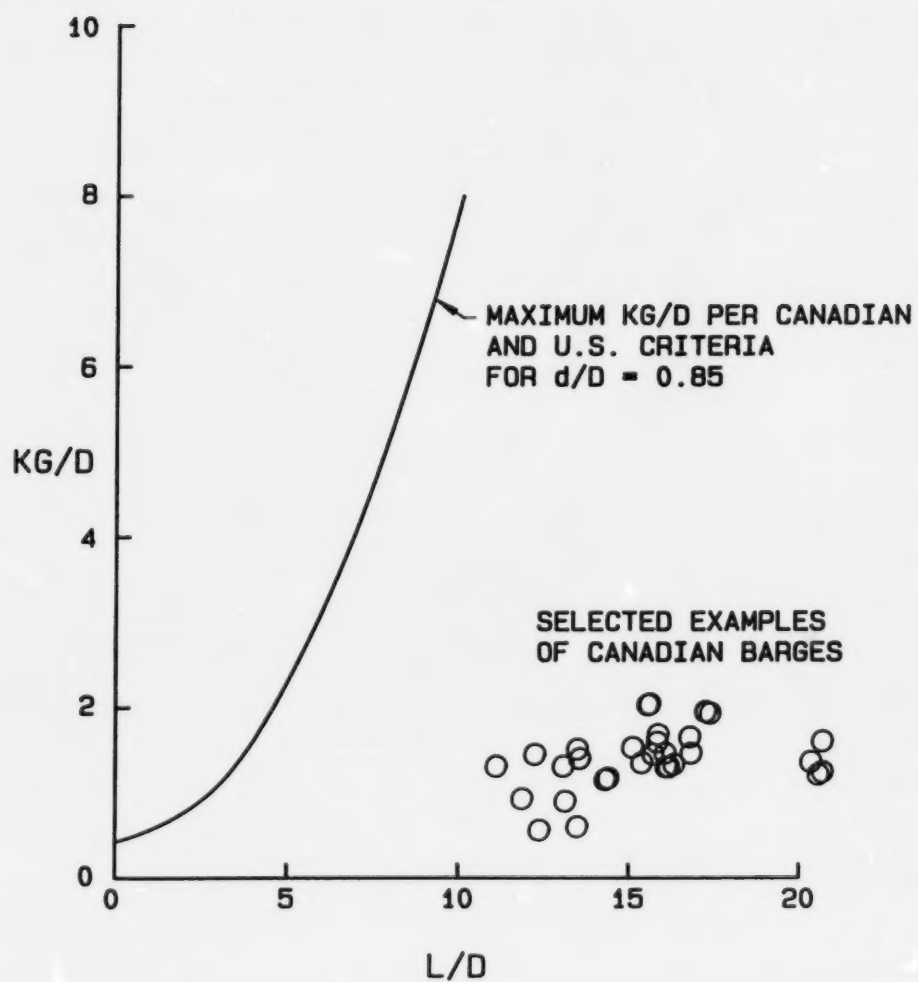


FIG. 17. LONGITUDINAL STABILITY
CRITERIA: KG/D vs. L/D

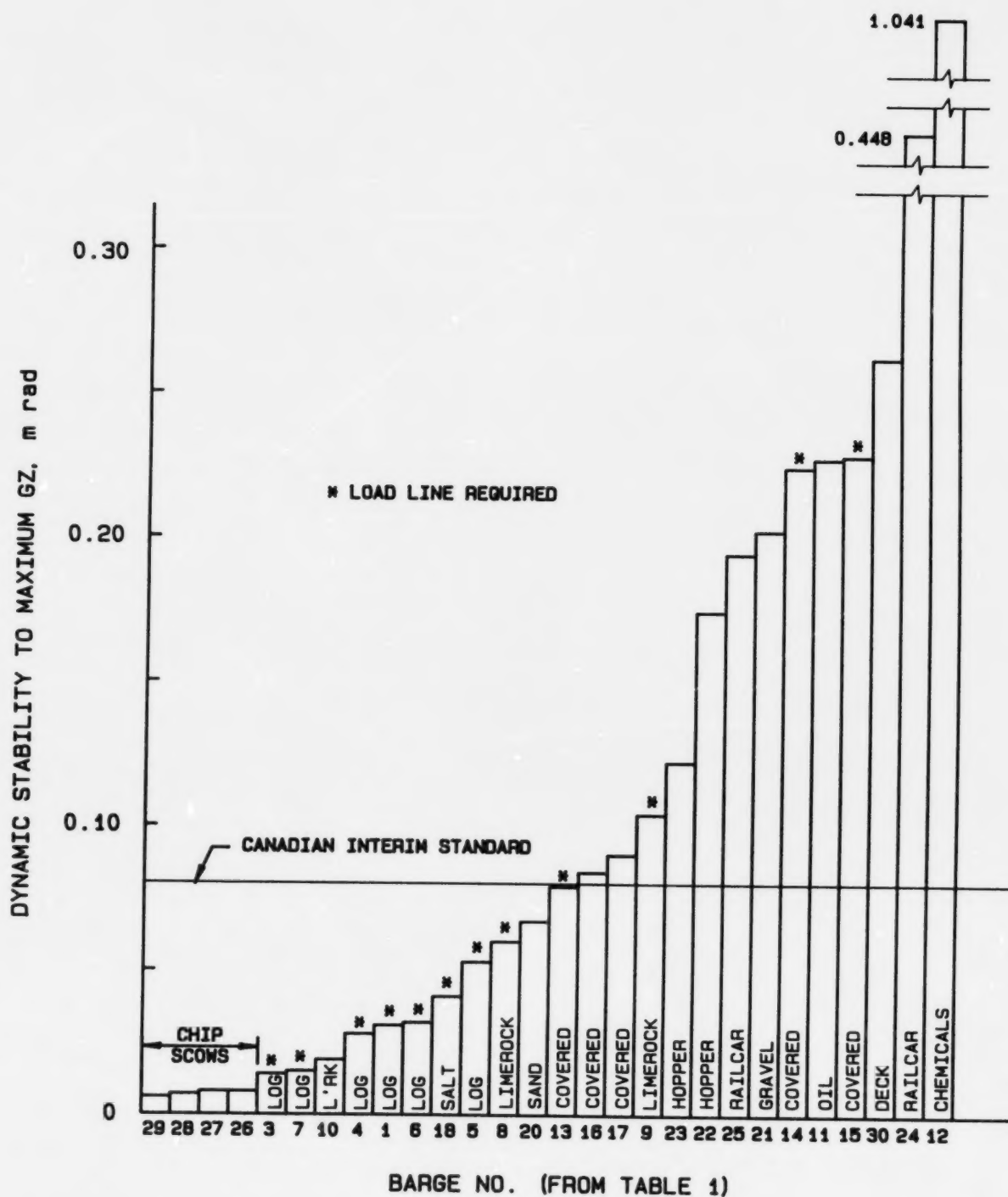


FIG. 18. DYNAMIC STABILITY OF SELECTED BARGES

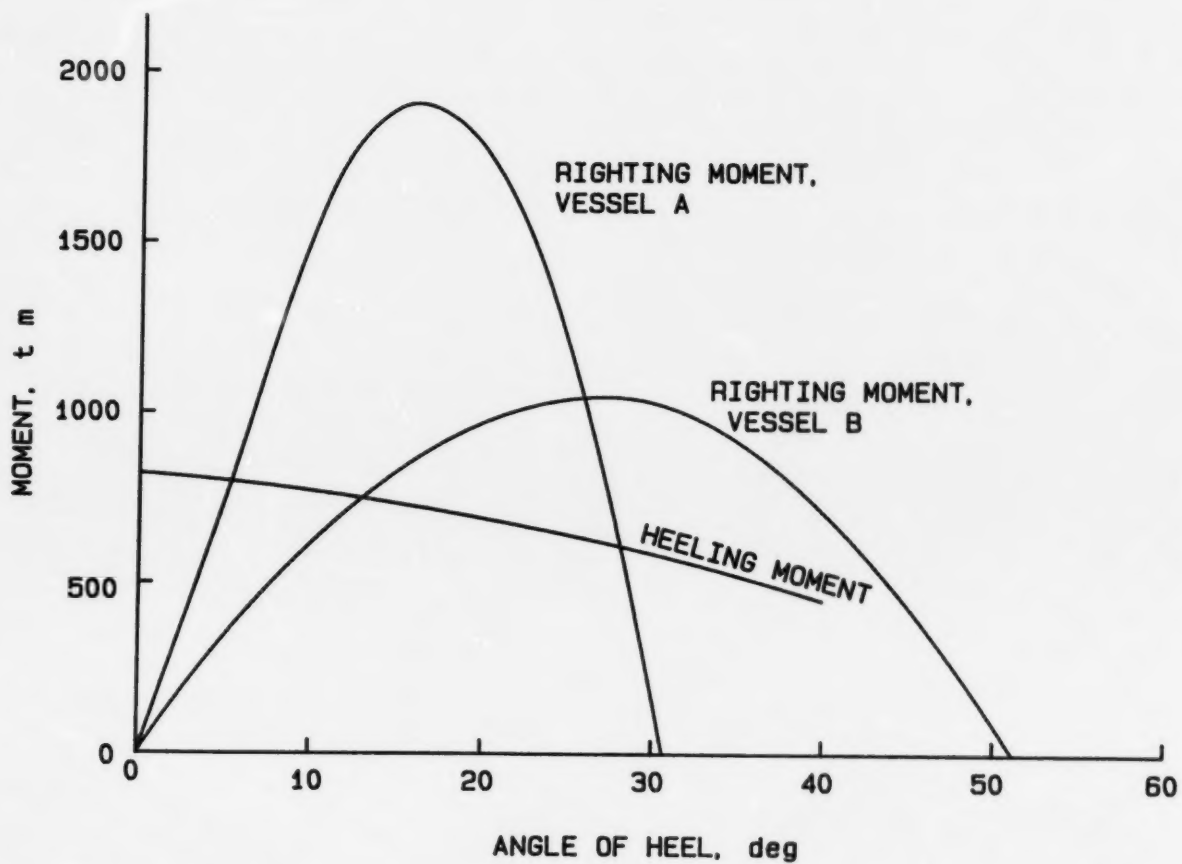


FIG. 19. RIGHTING AND HEELING
MOMENT CURVES

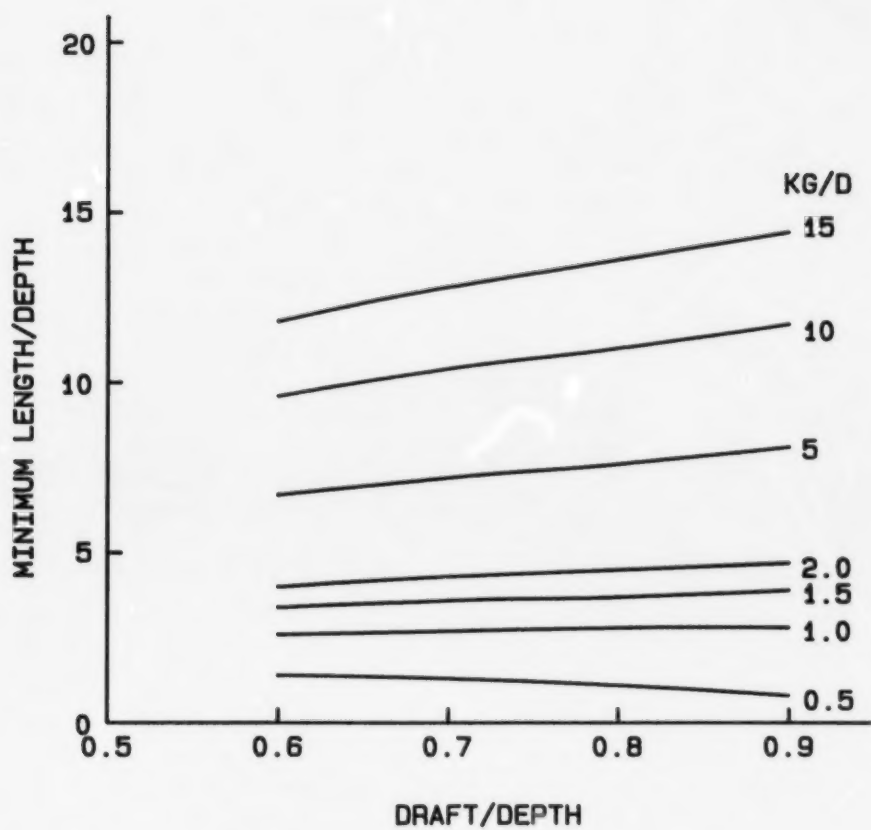


FIG. 20. LONGITUDINAL STABILITY CRITERION:
MINIMUM LENGTH/DEPTH vs. DRAFT/DEPTH

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BARGE NO.	TYPE	CARGO	DIMENSIONS, M						
			LOA	BEAM	DEPTH	DRAFT	DWT, T	DISPL, T	KG, M
1	Deck	Log	138.13	29.26	8.23	6.10	17374	21398	13.62
2	Deck	Log	120.78	26.82	7.62	5.79	12941	16101	12.81
3	Deck	Log	110.64	24.38	7.32	5.67	10727	13191	11.22
4	Deck	Log	110.95	24.38	7.01	5.18	9898	12001	11.18
5	Deck	Log Bundle	107.66	24.00	7.00	5.35	9437	11887	9.43
6	Deck	Log	112.47	23.16	7.16	5.18	9246	11679	10.35
7	Deck	Log	105.19	21.34	6.55	5.03	7849	9779	9.58
8	Deck	Limerock	109.05	24.38	7.62	6.02	11532	13592	8.78
9	Deck	Limerock	109.73	22.86	7.62	5.58	9784	11807	8.95
10	Deck	Limerock	57.91	15.24	4.27	3.51	2267	2772	5.99
11	Tank	Oil	82.30	18.29	6.10	4.88	4927	6004	3.66
12	Tank	Chemicals	83.06	19.51	6.71	4.57	4580	5950	3.75
13	Covered Deck	Newsprint	110.64	24.99	6.78	4.57	6533	9073	9.00
14	Covered Deck	Newsprint	109.12	24.99	6.78	4.57	6533	9156	8.81
15	Covered Deck	Newsprint	108.51	23.77	6.71	4.34	6096	8511	8.72
16	Covered/Hopper	Cement	50.75	14.63	4.57	3.35	1560	2127	5.98
17	Covered Deck	Pulp/Paper	61.57	14.63	3.66	2.59	1376	1923	5.34
18	Deck	Salt	88.39	20.73	6.76	5.08	6893	8026	8.88
19	Deck	Bulk	63.40	16.46	5.18	4.66	3628	4284	7.52
20	Deck	Sand/Lime	65.84	17.07	4.88	3.73	3225	3855	7.35
21	Deck	Gravel	60.96	15.24	2.95	2.27	1450	1909	3.66
22	Hopper	Clinker	80.16	18.90	6.10	4.74	4785	6268	5.50
23	Hopper	Cement	57.91	14.02	4.88	3.66	2118	2590	4.55
24	Deck	Railcar	103.33	19.51	5.03	2.44	2866	4303	6.10
25	Deck	Railcar	80.47	14.02	3.96	2.44	1632	2174	5.40
26	Deck	Chip	63.09	15.24	3.66	3.11	2311	2768	7.14
27	Deck	Chip	63.58	15.24	3.66	3.11	2307	2827	7.05
28	Deck	Chip	53.34	14.63	3.43	2.92	1768	2132	6.96
29	Deck	Chip	51.21	14.02	3.28	2.80	1560	1888	6.69
30	Deck	General	60.96	14.63	2.95	1.83	1425	1767	4.72

TABLE 1. EXAMPLES OF CANADIAN BARGES (SOURCE: ROBERT ALLAN LTD.)

ROBERT ALLAN LTD.
NAVAL ARCHITECTS

BARGE NO.	TYPE	CARGO	MAX. DWT	DYNAMIC STABILITY TO MAX. GZ
1	Deck	Lumber	16,300 t	0.114 m rad
2	Deck	General	10,000	0.140
3	Deck	Limerock	12,200	0.066
4	Covered	Pulp	2,100	0.104
5	Deck	Lumber	6,800	0.080
6	Deck	Aggregate	3,300	0.019

TABLE 2. DYNAMIC STABILITY OF SIX BARGES (FROM WARD [2])

ROBERT ALLAN LTD
NAVAL ARCHITECTS

BARGE NO.	TYPE	CARGO	MAX. DWT	DYNAMIC STABILITY TO MAX. GZ
7	Deck	Limerock	11,800 t	0.065 m rad
8	Covered	Pulp	2,000	0.074
9	Deck	Wood chips	2,300	0.162
10	Deck	Lumber	6,400	0.087

TABLE 3. DYNAMIC STABILITY OF FOUR BARGES (FROM WARD [45])

Atlantic Coast	19
Inland (Great Lakes and Mackenzie River)	153
Pacific Coast	461
TOTAL	633

TABLE 4. NUMBER OF CANADIAN BARGES, 1968

AREA	NO. OF BARGES	TOTAL DWT (t)
Atlantic Coast	30	54,000
Great Lakes	40	97,000
Mackenzie River	210	213,000
Pacific Coast	570	965,000
TOTAL	850	1,329,000

TABLE 5. CANADIAN BARGE FLEET, 1982

TYPE	NO. OF BARGES	TOTAL DWT	AVERAGE DWT
Flat deck	40	82,700 t	2,070 t
Covered deck	13	17,000	1,310
Bulk	9	85,800	9,530
Log	3	43,100	14,400
Tank	17	44,300	2,610
Chip	161	266,000	1,650
Railcar	8	13,200	1,650
TOTAL	251	552,100	2,200

TABLE 6. SEASPAN BARGE FLEET (Source: Seaspan International Ltd., 1982)

ROBERT ALLAN LTD.
NAVAL ARCHITECTS

TYPE	NO. OF BARGES	TOTAL DWT	AVERAGE DWT
Flat deck	21	28,900 t	1,380 t
Covered deck	4	6,000	1,500
Bulk	5	24,700	4,940
Log	4	27,800	6,950
Tank	4	5,300	1,320
Chip	34	41,400	1,220
Other	8	4,300	540
TOTAL	80	138,400	1,730

TABLE 7. RIVTOW BARGE FLEET (Source: RivTow Straits Limited, 1982)

TYPE OF CASUALTY	75	76	77	78	79	80	81	82	TOTAL
Collision	5	7	7	9	13	10	15	5	71
Grounding	4	2	2	3	2	2	13	2	30
Sinking	2	1	4	5	1	5	5	0	23
Capsized/stability	4	2	2	1	2	0	3	1	15
Fire, explosion	0	0	3	0	0	1	1	1	6
Weather or ice damage	0	1	0	1	0	1	2	0	5
TOTAL	15	13	18	19	18	19	39	9	150
NOTE: Period covered is February 8, 1975 to June 7, 1982. Source: Transport Canada, Canadian Coast Guard.									

TABLE 8. NUMBER OF BARGE CASUALTIES BY TYPE AND YEAR

VESSEL NAME	TYPE	YEAR BUILT	LENGTH (m)	BEAM (m)	DEPTH (m)	CASUALTY DATE	CARGO TYPE	STATEMENT
1. M.B.D. No. 32	Pilling	1960	36.6	12.2	3.07	75-02-15	--	Two men killed when shifting caisson caused capsizing
2. FMC 100	RRY/Tank	1966	51.2	13.7	3.07	75-02-19	Chem	Capsized with loss of cargo
3. Plymouth	Dry Cargo	1965	68.6	15.9	5.82	75-03-29	Sand	Barge sank in heavy seas
4. Seaspun 194	Dump Scow	1970	63.4	16.5	5.21	75-12-06	Lime	Barge towed to Vancouver, righted and repaired
5. Plymouth	Dry Cargo	1965	68.6	15.9	5.82	76-05-03	Sand	Unmanned barge, sank by bow
6. G.L.B. No. 1	Derrick	1953	88.4	--	--	76-08-01	Steel Pl	Cause of capsizing unknown, barge later raised
7. Seaspun 193	Flat Deck	1976	71.9	16.5	4.57	77-01-02	Shrd Steel	Cause of capsizing unknown
8. Millbanke V	Dry Cargo	1951	29.6	11	2.95	77-08-13	Salmon	Lost cargo after developing list, deckhouse damaged
9. Powell Carrier	Flat Deck	1954	104.5	19.2	5.97	78-02-12	Logs	Part cargo lost overboard due to severe weather
10. (No name)	Construction	--	--	--	--	79-08-26	None	Scow developed list and crane fell into dock
11. (Chaland)	Flat Deck	--	24.3	--	--	79-10-03	--	Loss of stability of barge
12. Trio Trader	Dry Cargo	--	--	--	--	81-01-14	Steel	Barge capsized and sank heading for Florida
13. McAsphalt 201	Tank	1968	81.1	--	--	81-08-31	Tar	Aft ballast tank flooded and stern sank in dock
14. Evco No. 3	Dump Scow	1967	60	14.1	4.33	81-12-22	Sand	Barge capsized 1.5 miles off Gowlland Pt.
15. Mack 4	Dump Scow	1951	28.4	10.4	2.96	82-02-19	--	Vessel reported sunk - total loss

Sources: 1. "Non-Propelled Barges Involved in Casualties as Reported to Transport Canada", Canadian Coast Guard, Ottawa, May 8, 1971 and November 19, 1982.
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ROBERT ALLAN LTD.
NAVAL ARCHITECTS

APPENDIX 1 - CANADIAN INTERIM BARGE STABILITY STANDARD

INTERIM STANDARD : STAB. 8

STANDARD FOR THE INTACT STABILITY OF UNMANNED CARGO BARGES

- (1) The provisions of this standard are applicable to unmanned cargo barges that:
 - (a) are required by standard Load 2 to be assigned loadlines; and
 - (b) are constructed after 1 September 1977
- (2) This standard does not apply to Crane, Derrick or Hopper Barges.
- (3) Except where otherwise exempted by the Board, the owner of a new barge shall:
 - (a) arrange to have an inclining experiment carried out in the presence of and to the satisfaction of a marine surveyor;
 - (b) submit to the Board the developed stability data for the operating conditions of the barge, including the light, loaded and worst operating conditions; and
 - (c) include in the stability submission, the basic data required by section 2 of standard STAB. 2.
- (4) Except where otherwise provided in Section 5 of this standard, the intact transverse stability of the barge shall be based upon a minimum area under the GZ curve up to the angle of maximum GZ, or to the angle of downflooding if this be less, of not less than 0.08 metre radians.
- (5) Where the vertical centre of gravity of the cargo is below the deck at side, the required transverse stability may be determined in terms of the metacentric height in metres. The initial metacentric height at any draft must not be less than that given by the following formula:

$$GM = \frac{kB}{f_e}$$

where $k = .15$

B = Beam in metres

f_e = Effective freeboard ($f + f_a$) in metres, where

f = freeboard to the deck at side in metres;
 f_a = additional freeboard allowance for barges having a structural watertight trunk.

$f_a = 1.25 \frac{hl}{L} \left(\frac{2b}{B} - 1 \right)$ or h , whichever is less. Appendix 1.
Page 2.

l = length of trunk in metres
 L = overall length of barge in metres
 b = breadth of trunk in metres
 h = trunk height at side in metres

- (6) The intact longitudinal stability of the barge is to be determined in terms of the minimum longitudinal metacentric height (GM_L) within the range of operating drafts and is not to be less than that given by the following formula:

$$GM_L = \frac{.02 L^2}{d} \text{ metres}$$

where L = overall length of barge in metres
 d = draft in metres.

APPENDIX 2 - BARGE CASUALTY DESCRIPTIONS

The barge casualties in Table 8 do not necessarily involve insufficient stability. Rather, they are those casualties in the 150 reported by the Coast Guard for which stability cannot be ruled out as a contributing factor. A brief discussion of each casualty follows:

1. "M.B.D. No. 32". A shifting caisson is blamed for causing the capsize of this barge. Weather conditions are unknown, but the capsize occurred in Saanich Inlet, a well protected body of water near Victoria, B. C. It is not known what caused the caisson to shift or whether a more stable barge would not have capsized. Two men were killed, the only fatalities known in connection with barge stability.
2. "FMC 100". This barge carried four rail tank cars on deck, each containing approximately 77 t of chlorine. About 620 t of liquid caustic soda were carried in tanks below deck. The vessel departed Squamish, B.C. under tow at 1730 PST on February 18, 1975. The tow continued through the night, proceeding up the Malaspina Strait. At about 0600 the following morning, the crew noticed the barge had capsized. Time of capsize was estimated at between 0400 and 0600. The railcars were lost and the caustic leaked into the sea. An intensive search by the Ministry of Transport failed to locate the tank cars. Sea state was described as moderate, with a following or quartering wind of about 40 km/hour. The cause of capsize remains a mystery.
3. "Plymouth". In the first of two incidents involving the same barge, the "Plymouth", a bulk self-unloader, capsized while carrying about 3,600 t of sand fill. Wind was described by the tug skipper as "strong gale westerly - 85 kn" (160 km/h) with the sea state as "very rough". As the last port of departure was Friday Harbor, Washington, and the capsize occurred in the Strait of Georgia, the tow was presumably taking the seas head on, or slightly off the bow. Clearly, heavy weather was a contributing factor.
4. "Seaspan 194" (ex "G. of G. 500"). This vessel overturned while carrying 4,200 t of crushed limerock. The tug skipper's report describes a choppy sea with wind out of the southeast at 15 knots (28 km/h). The report puts the location as "Georgia Strait", three miles west of Bertha Island". The Coast Guard computer listing, however, gives a location about 800 km to the northwest. As the tow was en route from Beal Cove, B.C. to Vancouver, the skipper's position may be taken as more accurate. Again, the tow was presumably heading into the seas.
5. "Plymouth". Barely one month after the capsize mentioned in incident number 3 above, the "Plymouth" foundered off Orcas Island in the south end of Georgia Strait. Cargo was reported as about 7,200 t of sand, although the deadweight capacity of this barge is only about half that amount.

6. **"G.L.B. No. 1".** While carrying 2,410 t of steel slabs, this barge capsized and later sank in northern Lake Huron. The casualty report, signed by the tug's chief engineer, gives the weather as "light winds from west" and a sea state of "1 - 2 ft. from west". The report continues:

"Barge apparently struck obstruction while on passage and under tow and developed starboard list. Men put aboard to pump. List worsened and men removed. Shortly afterwards barge capsized and returned to surface upside down. Cargo and crane lost. Barge towed toward U.S. shore and sank in position 45°13'45"N, 83°20'45"W. Raised by salvage 25 Sept. 1971 and towed to Rockport, Michigan."

This incident is included to illustrate the contribution of taking on water to barge capsizing. It is unlikely that a cargo of steel slabs would be stowed with a high KG. Furthermore, 2,410 t would probably be a light load for this 88 m long barge. All indications are that the intact stability of this barge was adequate; capsize, by itself, does not imply inadequate stability.

7. **"Seaspan 193".** While under tow and laden with about 3,160 t of shredded steel, this barge capsized in southern Georgia Strait. Sea state, by the tug master's report, was choppy. Wind was ENE at 12 - 15 kn (22 - 28 km/h). Bound from Vancouver for Tacoma, the wind and seas would have been approximately abeam. Cause is unknown.
8. **"Millbanke V".** The master's casualty report was not available for this incident. The Coast Guard data statement reads, "Lost cargo after developing list. Some damage to deckhouse". Wind is reported as 5 knots from the southwest, the sea slight to moderate.

Location is given as near Pine Island in southern Queen Charlotte Sound. The cause of the list is not reported. However, given the good weather conditions, it is reasonable to suppose that either the barge took on water or the cargo (salmon) was not properly secured and shifted.

9. **"Powell Carrier".** This large (104 m) barge lost part of her 4,100 t of lumber cargo off Monterey Bay, California. She was bound for Long Beach, California from Vancouver, B.C. The master's account reads:

"The tug and tow experienced rough seas and heavy swells with the wind rising to southerly 80 knots (150 km/h) and gusting. This abnormally severe weather caused the cargo to shift to starboard against the sidewall and the barge subsequently dumped part of her load."

10. **(No name.)** This 14 m long construction scow was in harbour in Goderich, Ontario, on Lake Huron. The Coast Guard statement reads, "Scow developed list and crane fell into dock". Stated cause of the incident is "Other vessels and 3rd party cause/error". Wind at the time was calm and the sea smooth. No cargo was aboard.

When an empty scow in harbour develops a list, one can presumably rule out improper cargo loading or heavy seas. This does not appear to be an incident which any reasonable stability regulations could have prevented.

11. (Chaland.) "Chaland" is French for barge and probably not the name of this vessel. Information concerning this incident is scant. The Department of Transport shipping casualty report form, usually signed by the master, is unsigned. It states only that the 24 m barge suffered a "perte d'equilibre" (loss of stability), in the Baie de Tadoussac on the St. Lawrence River. Four persons are listed as injured. The nature and extent of their injuries, or other details concerning the incident, are unknown.
12. "Trio Trader". While carrying an unknown quantity of steel, this barge capsized and sank in the Gulf of Maine, about 200 km southwest of Cape Sable Island. Wind was reported as 20 km/hour from the southwest. As the tow was en route to Florida at the time, the wind was presumably on the starboard bow. Again, no further details are known. Given the dense cargo and moderate weather, one can suppose that taking on water through leakage may have been a factor.
13. "McAsphalt 201". In the calm water of St. Mary's River, inland from Sault Ste. Marie, this vessel's "after ballast tank flooded and stern sank to bottom of dock." The cause of the ballast tank's flooding is unknown. Conceivably, the barge was improperly loaded with her cargo of tar and lost enough stability to submerge a hatch to the tank. But then the hatch must have been improperly secured. Other, more likely explanations including inadvertent opening of the tank valves and unknown leakage into the tank. This example is included only because insufficient intact stability cannot be ruled out.
14. "Evco No. 3". This 60 m dump scow, loaded with sand, capsized in Boundary Pass in the Haro Strait area of coastal B.C. Wind was 28 km/h from the southeast; seas are described as moderate. No other details are known of this incident.
15. "Mack 4". Another dump scow, 28 m long, the "Mack 4" was reported sunk in the Juan de Fuca Strait, just south of Victoria, B.C. Details regarding weather, cargo, and cause of the sinking are not reported. As in the case of "McAsphalt 201", a lack of intact stability can be neither confirmed nor ruled out.

APPENDIX 3 - ANALYSIS OF GM - FREEBOARD CRITERION

Let

$$\begin{aligned}r &= B/D \\s &= d/D\end{aligned}$$

where

$$\begin{aligned}B &= \text{Beam, metres} \\D &= \text{Depth, metres} \\d &= \text{Draft, metres}\end{aligned}$$

Minimum required GM = GM_r

$$GM_r = kB/f_e, \text{ per [56] and 46 CFR 151.10-5}$$

Assume a barge with $KG = D$. This is the most conservative case, since to apply this criterion, the cargo vertical centre of gravity must be below the deck. Further assume no trunk.

Then

$$\begin{aligned}f_e &= f = D - d \\f/D &= \frac{D - d}{D} = 1 - s\end{aligned}$$

$$GM_r = \frac{kB}{f} = k \left(\frac{B/D}{f/D} \right) = k \left(\frac{r}{1-s} \right)$$

Actual GM = GM_a

$$GM_a = KB + BM - KG, \text{ assuming no free surfaces}$$

$$KB = d/2, \text{ approximately}$$

$$BM = I_t/V = \frac{(1/12) L (.98B)^3}{C_b L B d}, \text{ approximately}$$

Taking $C_b = .86$,

$$BM = .0912B^2/d$$

$$KG = D, \text{ as assumed above}$$

$$\begin{aligned}\text{Then } GM_a &= d/2 + 0.0912B^2/d - KG \\ &= D(0.5s + 0.0912r^2/s-1)\end{aligned}$$

For a barge which just meets the criterion,

$$\begin{aligned}GM_a &= GM_r \\ (0.5s + 0.0912r^2/s-1) &= kr/(1-s)\end{aligned}$$

Using $k = 0.15$ per [58], this reduces to:

$$D = \frac{0.15r}{(1-s)(0.5s + 0.0912r^2/s - 1)}$$

A graph of the solution to this equation is shown in Figure 16.

APPENDIX 4 - ANALYSIS OF LONGITUDINAL STABILITY CRITERIA

The Canadian and U.S. criteria both require

$$\text{minimum } GM_1 = 0.02 L^2/d \quad [58] \text{ and } 46 \text{ CFR } 151.10-6$$

For a barge

$$\text{available } GM_1 = KB + BM_1 - KG$$

Assume

$$KB = d/2$$

By definition,

$$BM_1 = \frac{I_1}{V} = \frac{I_1}{LBdC_b}$$

Let

L_e = length of rectangle of breadth B which has the same I_1 as the barge waterplane; sometimes called "effective length".

Then

$$I_1 = B (L_e)^3/12$$

Assume

$$L_e = 0.95L \text{ and}$$

$$C_b = 0.86$$

Hence

$$BM_1 = \frac{B (0.95L)^3/12}{.86 L B d}$$

$$= 0.0831 L^2/d$$

$$\text{Available } GM_1 = d/2 + 0.0831 \frac{L^2}{d} - KG$$

Now let

$$s = d/D$$

$$t = KG/D$$

$$u = L/D$$

Setting available GM_1 = minimum GM_1 , we have

$$d/2 + 0.0831 L^2/d - tD = 0.02 L^2/d$$

Collecting terms and dividing by D,

$$0.0631 u^2/s = t - s/2$$

$$u = \sqrt{7.93 s (2t - s)}$$

Figure 20 shows a plot of this function. This plot may be thought of as the minimum required L/D for a barge, given KG/D and d/D , to meet the GM_1 criteria. As the results are relatively independent of d/D , a representative value of $d/D = .85$ was chosen to develop Figure 17.

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